APPENDIX A

DATA USED IN THE CALCULATIONS

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DATA USED IN THE CALCULATIONS

This appendix summarizes the parameters and models used to calculate potential intakes of hazardous materials and convert them to radiation dose or some type of severity index for the various exposure scenarios. What follows is a description of each parameter, typical values, and the justification for the values chosen. Where these parameters differ from prior performance assessments for Hanford disposal sites, the differences are explained. The mathematical models are described to illustrate how the parameters are used in calculations.

For the most part this Revision 3 updates various parameters for radionuclides and chemicals from those released as Revision 2. The principle changes are to the soil-to-plant concentration ratios and the chemical toxicity factors. In addition, the soil model was revised to include volatile emissions of chemicals. The discussion of data and models is divided into several topical areas, namely, nuclear and chemical properties, human activities, animal, plant, and soil characteristics.

An additional consideration is the potential effects on special groups of individuals who may be exposed in unique ways not normally considered. Information relevant to estimating the dose received by these special groups is included in each section.

A1.0 NUCLEAR PARAMETERS

The first parameters of interest are basic nuclear properties of the radionuclides that may be found in waste buried on the Hanford Site. The two main selection criteria for these nuclides are the radioactive half-life and the projected inventory in typical N-Reactor fuel. Radionuclides with half-lives greater than approximately one year are considered. If the nuclide is listed as a constituent in the waste stored in underground tanks or the burial grounds, it was included in the list.

Table A1 shows the decay half-life and the decay chain branching ratios. A branching ratio is the fraction of decays of a parent nuclide that produce a given progeny nuclide. These parameters are needed to determine the amount of a nuclide, and any radioactive progeny, that is present as a function of time. Values are taken from the Evaluated Nuclear Data File, Release VI (ENDF/B-VI). The conversion from seconds to years was carried out using the value 365.25 days per year.

Also shown on Table A1 are the short-lived progeny that are assumed to be in secular equilibrium with the parent. These short half-life progeny are also called "implicit daughters" because their radioactive emissions are not considered separately, but combined with the parent nuclide. When referring to the activity of these groups of nuclides, only the activity of the first member of the decay chain is shown. It is understood that there is additional activity in the progeny nuclides. For example, 1 Ci of Sr-90+D means 1 Ci Sr-90 and 1 Ci Y-90.

Table A1. Radionuclides to be Considered and Their Half Lives.

Nuclide	Half life (y)	Short-lived progeny in equilibrium with parent
H-3	12.33	
Be-10	1.600E+06	
C-14	5,730	
Na-22	2.6019	
Al-26	719,985	
Si-32+D	329.56	P-32
Cl-36	300,992	
K-40	1.277E+09	
Ca-41	102,999	
Ti-44+D	47.30	Sc-44
V-49	0.92539 (338 d)	
Mn-54	0.85454 (312.12 d)	
Fe-55	2.7299	
Fe-60	1,500,000	Co-60m
Co-60	5.2713	
Ni-59	74,999	
Ni-63	100.10	
Se-79	805,000	
Rb-87	4.800E+10	
Sr-90+D	28.149	Y-90
Zr-93	1.530E+06	
Nb-91	680	
Nb-93m	16.13	
Nb-94	20,300	
Mo-93	3,500	
Tc-99	211,097	
Ru-106+D	1.01736 (371.59 d)	Rh-106
Pd-107	6.50E+06	
Ag-108m+D	127.00	Ag-108 (0.087)
Cd-109	1.26653 (462.6 d)	
Cd-113m	14.10	
In-115	4.410E+14	
Sn-121m+D	54.998	Sn-121 (0.776)
Sn-126+D	246,000	Sb-126m, Sb-126 (0.14)
Sb-125	2.7299	
Te-125m	0.15880 (58 d)	
I-129	1.570E+07	
Cs-134	2.0619	
Cs-135	2.30E+06	
Cs-137+D	29.999	Ba-137m (0.9443)
Ba-133	10.520	
Pm-147	2.6233	
Sm-147	1.060E+11	
Sm-151	89.997	
Eu-150	35.798	
Eu-152	13.330	
Eu-154	8.5919	
Eu-155	4.680	
Gd-152	1.080E+14	
Ho-166m	1,200	
Re-187	5.000E+10	
Tl-204	3.7801	
Pb-205	1.520E+07	

Table A1. Radionuclides to be Considered and Their Half Lives.

Nuclide	Half life (y)	Short-lived progeny in equilibrium with parent
Pb-210+D	22.300	Bi-210
Bi-207	32.198	
Po-209	102.0	
Po-210	0.37886 (138.38 d)	
Ra-226+D	1,600	Rn-222, Po-218, Pb-214, Bi-214, Po-214(0.9998)
Ra-228+D	5.7498	Ac-228
Ac-227+D	21.769	Th-227(0.9862), Fr-223(0.0138), Ra-223, Rn-219, Po-215, Pb-211, Bi-211, Tl-207(.99725), Po-211(.00275)
Th-228+D	1.9129	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Po-212(0.6406), Tl-208(0.3594)
Th-229+D	7,340	Ra-225, Ac-225, Fr-221, At-217, Bi213, Po-213(0.9784), Tl-209(0.0216)
Th-230	75,380	
Th-232	1.405E+10	
Pa-231	32,759	
U-232	69.799	
U-233	159,198	
U-234	245,694	
U-235+D	7.037E+08	Th-231
U-236	2.342E+07	
U-238+D	4.468E+09	Th-234, Pa-234m, Pa-234 (0.0013)
Np-237+D	2.140E+06	Pa-233
Pu-236	2.8999	
Pu-238	87.697	
Pu-239	24,110	
Pu-240	6,563	
Pu-241+D	14.350	U-237 (2.39E-05)
Pu-242	373,507	
Pu-244+D	8.000E+07	U-240 (0.9988), Np-240m, Np-240 (0.0012)
Am-241	432.70	
Am-242m+D	141.00	Am-242(0.9955), Np-238(0.0045)
Am-243+D	7,370	Np-239
Cm-242	0.44611 (162.94 d)	
Cm-243	28.499	
Cm-244	18.100	
Cm-245	8,500	
Cm-246	4,730	
Cm-247+D	1.600E+07	Pu-243
Cm-248	339,981	
Cm-250+D	11,300	Pu-246(0.25), Am-246(0.25), Bk-250(0.14)
Bk-247	1,394	
Cf-248	0.91294 (333.45 d)	
Cf-249	350.60	
Cf-250	13.080	
Cf-251	897.98	
Cf-252	2.6449	

Notes:

- Parentheses in the second column show half-lives that are normally given in days.
- Parentheses in the third column show branching ratios that differ from 1.00. Short-lived progeny are radionuclides that are normally found in secular equilibrium with the parent nuclide. They typically have half-lives less than 30 days.
- Half-lives and branching ratios are from ENDF/B-VI, except for Se-79 and Sn-126. See DOE/ORP-2000-24 Revision 0, Section 3.2.2 for discussion of revisions to the half lives for Se-79 and Sn-126.

As noted in DOE/ORP-2000-24 Revision 0, *Hanford Immobilized Low-Activity Tank Waste Performance Assessment* (section 3.2.2), new measurements of the half-lives for Se-79 and Sn-126 show substantial increases. References for the revised half lives are Chu, et al. (1998), Chunsheng, et al. (1997), Yu, et al. (1993), and Zhang, et al. (1996). The newer values have been used in Table A1.

Table A2 shows the radioactive decay chains included in the exposure scenario calculations. Radioactive decay normally reduces the dose that a receptor could receive. However, in the cases shown on Table A2, the in-growth of the progeny nuclides with time may increase the dose from the parent nuclide. One example of this is Th-232, which has a very long half-life so that there is essentially no change in its activity during the year of exposure. Since the initial activity of the progeny nuclides (Ra-228 and Th-228) is assumed to be zero any increase will have maximum effect on the Th-232 doses. In addition, since the progeny accumulate according to their much shorter half-lives, they are able to increase the dose from Th-232 significantly.

The decay chains used in these calculations are limited to four radioactive members by the assumption that the decay times involved in the generation of unit dose factors will be less than 1000 years. At longer decay times, the ingrowth of progeny farther down the chain may be important. The longest decay times used in this report is 70 years.

Table A2. Decay Chains Actually Computed.

Fe-60	→ .9976	Co-60				
Zr-93	→	Nb-93m				
Mo-93	→	Nb-93m				
Sb-125	→ .230	Te-125m				
Pm-147	→	Sm-147				
Eu-152	→ .2792	Gd-152				
Pb-210	→	Po-210				
Po-209	→ .9974	Pb-205				
Ra-226	→	Pb-210	→	Po-210		
Ra-228	→	Th-228				
Th-230	→	Ra-226	→	Pb-210	→	Po-210
Th-232	→	Ra-228	→	Th-228		
Pa-231	→	Ac-227				
U-232	→	Th-228				
U-233	→	Th-229				
U-234	→	Th-230	→	Ra-226	→	Pb-210
U-235	→	Pa-231	→	Ac-227		
Pu-236	→	U-232	→	Th-228		
Pu-238	→	U-234				
Pu-241	→	Am-241	→	Np-237		
Pu-244	→	Pu-240				

Table A2. Decay Chains Actually Computed.

Am-241	→	Np-237				
Am-242m	→	Cm-242	→	Pu-238	→	U-234
	↓ .827					
	→	Pu-242				
	.173					
Am-243	→	Pu-239				
Cm-242	→	Pu-238	→	U-234		
Cm-243	→	Pu-239				
	↓					
	→	Am-243				
	.0024					
Cm-244	→	Pu-240				
Cm-245	→	Pu-241	→	Am-241	→	Np-237
Cm-247	→	Am-243				
Cm-250	→	Cf-250	→			
	↓ .14		↓			
	→	Cm-246	←			
	.25					
Bk-247	→	Am-243				
Cf-248	→	Cm-244	→	Pu-240		
Cf-249	→	Cm-245	→	Pu-241	→	Am-241
Cf-250	→	Cm-246				
Cf-251	→	Cm-247				
Cf-252	→	Cm-248				

Notes:
- Decay times are assumed to be less than 1000 years so that the in-growth of progeny with long half-lives can be ignored.
- There is a slight increase in the Pu-238 and U-234 for the Am-242m decay chain that is not shown. This is a result of the low-probability alpha decay of Am-242m. The complete chain is, Am-242m(0.00455)--->Np-238--->Pu-238--->U-234.

A2.0 CHEMICALS OF INTEREST

The list of hazardous chemicals used in the generation of unit hazard quotients and unit risk factors comes from PNNL-12040, *Regulatory Data Quality Objectives Supporting Tank Waste Remediation System Privatization Project*, 1998. Table 4.4 lists 125 organic compounds and Table 4.7 lists 51 inorganic compounds that are recommended for characterizing Hanford underground tank waste. In addition, Appendix B lists 1,227 compounds from the TWINS database. Of these, there are 410 compounds listed with at least 10 vapor hits or at least one solid/liquid hit.

The lists found in PNNL-12040 were compared with the list of chemicals for which there is toxicological data according to the Risk Assessment Information System (RAIS). The Oak Ridge National Laboratory (ORNL) maintains this toxicological data listing for human health risk assessments. The data may be obtained from the World Wide Web using the location http://risk.lsd.ornl.gov. The values that were current as of June, 2003 were used for unit risk factors in the present document. The list of chemicals that are found in either the 410-chemical list (Table B.1 of PNNL-12040) or the 176-chemical list (Tables 4.4 and 4.7 of PNNL-12040) was compared with the 695-chemical RAIS database. The 126 common chemicals are shown in Table A3 along with the Chemical Abstract Service Reference Number (CASRN).

It is unlikely that any hazardous chemical has been omitted from the detailed study documented in PNNL-12040. In addition, it is assumed that the toxic materials of concern have been studied sufficiently that appropriate measures of their toxicity are available. It may be that serious toxins have not been studied in such detail at this point in time. The list given in Table A3 represents the most complete information available at the present time. The molecular weights, water solubilities, unitless Henry's Law constants, and logarithms of the octanol-water constants are from the EPA software EPI Suite™ Version 3.10. The application of these parameters is discussed in later sections.

Table A3. List of Chemicals.

CASRN	Chemical	Molecular Weight (g/mole)	Solubility in Water (mg/L)	Unitless Henry's Law Constant	$Log(K_{OW})$
50-32-8	Benzo[a]pyrene	252.32	1.62E-03	1.87E-05	6.13
53-70-3	Dibenz[a,h]anthracene	278.36	2.49E-03	5.03E-06	6.75
56-23-5	Carbon tetrachloride	153.82	7.93E+02	1.13E+00	2.83
57-12-5	Cyanide, free	27.03	1.00E+06	5.44E-03	-0.25
57-14-7	1,1-Dimethylhydrazine	60.10	1.00E+06	2.84E-06	-1.19
57-55-6	Propylene glycol (1,2-Propanediol)	76.10	1.00E+06	5.35E-09	-0.92
58-89-9	gamma-Benzene hexachloride (gamma-Lindane)	290.83	7.30E+00	2.10E-04	3.72
60-34-4	Methylhydrazine	46.07	1.00E+06	1.29E-06	-1.05
60-57-1	Dieldrin	380.91	1.95E-01	4.09E-04	5.40
62-75-9	N-Nitrosodimethylamine	74.08	1.00E+06	7.44E-05	-0.57
64-18-6	Formic acid	46.03	1.00E+06	6.83E-06	-0.54
67-56-1	Methanol (Methyl alcohol)	32.04	1.00E+06	1.86E-04	-0.77
67-64-1	Acetone (2-Propanone)	58.08	1.00E+06	1.62E-03	-0.24
67-66-3	Chloroform	119.38	7.95E+03	1.50E-01	1.97
71-36-3	n-Butyl alcohol (n-Butanol)	74.12	6.32E+04	3.60E-04	0.88
71-43-2	Benzene	78.11	1.79E+03	2.27E-01	2.13
71-55-6	1,1,1-Trichloroethane (Methyl chloroform)	133.41	1.29E+03	7.03E-01	2.49
72-20-8	Endrin	380.91	2.50E-01	2.60E-04	5.20
74-83-9	Bromomethane	94.94	1.52E+04	2.55E-01	1.19
74-87-3	Methyl chloride (Chloromethane)	50.49	5.32E+03	3.61E-01	0.91
75-00-3	Ethyl Chloride	64.52	6.71E+03	4.54E-01	1.43
75-01-4	Vinyl chloride (Chloroethene)	62.50	8.80E+03	1.14E+00	1.62
75-05-8	Acetonitrile	41.05	1.00E+06	1.41E-03	-0.34
75-07-0	Acetaldehyde	44.05	1.00E+06	2.73E-03	-0.34
75-09-2	Dichloromethane (Methylene chloride)	84.93	1.30E+04	1.33E-01	1.25
75-15-0	Carbon disulfide	76.13	1.18E+03	5.89E-01	1.94
75-21-8	Ethylene Oxide (Oxirane)	44.05	1.00E+06	6.05E-03	-0.30

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Table A3. List of Chemicals.

CASRN	Chemical	Molecular Weight (g/mole)	Solubility in Water (mg/L)	Unitless Henry's Law Constant	Log(K_{OW})
75-34-3	1,1-Dichloroethane (Ethylidene chloride)	98.96	5.04E+03	2.30E-01	1.79
75-35-4	1,1-Dichloroethylene	96.94	2.42E+03	1.07E+00	2.13
75-45-6	Chlorodifluoromethane	86.47	2.77E+03	1.66E+00	1.08
75-68-3	Chloro-1,1-difluoroethane, 1-	100.50	1.40E+03	2.40E+00	2.05
75-69-4	Trichlorofluoromethane	137.37	1.10E+03	3.96E+00	2.53
75-71-8	Dichlorodifluoromethane	120.91	2.80E+02	1.40E+01	2.16
76-13-1	1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113)	187.38	1.70E+02	2.15E+01	3.16
76-44-8	Heptachlor	373.32	1.80E-01	1.20E-02	6.10
78-87-5	1,2-Dichloropropane	112.99	2.80E+03	1.15E-01	1.98
78-93-3	Methyl ethyl ketone (2-Butanone)	72.11	2.23E+05	2.33E-03	0.29
79-00-5	1,1,2-Trichloroethane	133.41	1.10E+03	3.37E-02	1.89
79-01-6	Trichloroethylene	131.39	1.28E+03	4.03E-01	2.42
79-10-7	2-Propenoic acid (Acrylic acid)	72.06	1.00E+06	1.51E-05	0.35
79-34-5	1,1,2,2-Tetrachloroethane (Acetylene tetrachloride)	167.85	2.87E+03	1.50E-02	2.39
82-68-8	Pentachloronitrobenzene (PCNB)	295.34	4.40E-01	1.81E-03	4.64
83-32-9	Acenaphthene	154.21	3.90E+00	7.44E-03	3.92
84-66-2	Diethyl phthalate	222.24	1.08E+03	2.49E-05	2.42
84-74-2	Dibutyl phthalate	278.35	1.12E+01	7.40E-05	4.50
85-68-7	Butyl benzyl phthalate	312.37	2.69E+00	5.15E-05	4.73
87-68-3	Hexachlorobutadiene	260.76	3.20E+00	4.21E-01	4.78
87-86-5	Pentachlorophenol	266.34	1.40E+01	1.00E-06	5.12
88-06-2	2,4,6-Trichlorophenol	197.45	8.00E+02	1.06E-04	3.69
88-85-7	2-sec-Butyl-4,6-dinitrophenol (Dinoseb)	240.22	5.20E+01	1.86E-05	3.56
91-20-3	Naphthalene	128.18	3.10E+01	1.80E-02	3.30
92-52-4	1,1'-Biphenyl	154.21	6.94E+00	1.26E-02	3.98
95-50-1	1,2-Dichlorobenzene (ortho-)	147.00	8.00E+01	7.85E-02	3.43
95-63-6	1,2,4-Trimethylbenzene	120.20	5.70E+01	2.52E-01	3.63
98-86-2	Acetophenone	120.15	6.13E+03	4.25E-04	1.58
98-95-3	Nitrobenzene	123.11	2.09E+03	9.81E-04	1.85
100-25-4	1,4-Dinitrobenzene (para-)	168.11	6.90E+01	1.51E-05	1.46
100-41-4	Ethyl benzene	106.17	1.69E+02	3.22E-01	3.15
100-42-5	Styrene	104.15	3.10E+02	1.12E-01	2.95
100-51-6	Benzyl alchohol	108.14	4.29E+04	1.38E-05	1.10
106-46-7	1,4-Dichlorobenzene (para-)	147.00	8.13E+01	9.85E-02	3.44
106-93-4	1,2-Dibromoethane (Ethylene dibromide)	187.86	3.91E+03	2.73E-02	1.96
106-99-0	1,3-Butadiene	54.09	7.35E+02	3.01E+00	1.99
107-02-8	Acrolein	56.06	2.12E+05	4.99E-03	-0.01
107-05-1	3-Chloropropene (Allyl chloride)	76.53	3.37E+03	4.50E-01	1.93
107-06-2	1,2-Dichloroethane (Ethylene chloride)	98.96	5.10E+03	4.82E-02	1.48
107-13-1	Acrylonitrile	53.06	7.45E+04	5.64E-03	0.25

Table A3. List of Chemicals.

CASRN	Chemical	Molecular Weight (g/mole)	Solubility in Water (mg/L)	Unitless Henry's Law Constant	Log(K_{OW})
108-10-1	Methyl isobutyl ketone (4-Methyl-2-pentanone)	100.16	1.90E+04	5.64E-03	1.31
108-67-8	1,3,5-Trimethylbenzene	120.20	4.82E+01	3.58E-01	3.42
108-87-2	Methyl cyclohexane	98.19	1.40E+01	1.76E+01	3.61
108-88-3	Toluene (Methyl benzene)	92.14	5.26E+02	2.71E-01	2.73
108-90-7	Chlorobenzene	112.56	4.98E+02	1.27E-01	2.84
108-94-1	Cyclohexanone	98.15	2.50E+04	3.68E-04	0.81
108-95-2	Phenol (Carbolic acid)	94.11	8.28E+04	1.36E-05	1.46
110-00-9	Furan (Oxacyclopentadiene)	68.08	1.00E+04	2.21E-01	1.34
110-54-3	n-Hexane	86.18	9.50E+00	7.36E+01	3.90
110-86-1	Pyridine	79.10	1.00E+06	4.50E-04	0.65
111-76-2	2-Butoxyethanol (Ethylene Glycol Monobutyl Ether)	118.18	1.00E+06	6.54E-05	0.83
111-90-0	2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether)	134.18	1.00E+06	9.11E-10	-0.54
117-81-7	Di (2-ethylhexyl) phthalate (DEHP)	390.57	2.70E-01	1.10E-05	7.60
117-84-0	Di-n-octylphthalate	390.57	2.00E-02	1.05E-04	8.10
118-74-1	Hexachlorobenzene	284.78	6.20E-03	6.95E-02	5.73
120-82-1	1,2,4-Trichlorobenzene	181.45	4.90E+01	5.80E-02	4.02
121-44-8	Triethylamine	101.19	7.37E+04	6.09E-03	1.45
122-39-4	Diphenylamine	169.23	5.30E+01	1.39E-04	3.50
123-91-1	1,4-Dioxane (Diethylene oxide)	88.11	1.00E+06	1.96E-04	-0.27
126-73-8	Tributyl Phosphate	266.32	2.80E+02	6.13E-06	4.00
126-98-7	2-Methyl-2-propenenitrile (Methacrylonitrile)	67.09	2.54E+04	1.01E-02	0.68
127-18-4	1,1,2,2-Tetrachloroethylene	165.83	2.06E+02	7.23E-01	3.40
141-78-6	Ethyl acetate (Acetic acid, ethyl ester)	88.11	8.00E+04	5.48E-03	0.73
156-59-2	cis-1,2-Dichloroethylene	96.94	4.52E+03	1.67E-01	1.86
206-44-0	Fluoranthene (1,2-Benzacenaphthene)	202.26	2.60E-01	3.62E-04	5.16
309-00-2	Aldrin	364.92	1.70E-02	1.80E-03	6.50
319-84-6	alpha-Benzene hexachloride (alpha-Lindane)	290.83	2.00E+00	4.99E-04	3.80
319-85-7	beta-Benzene hexachloride (beta-Lindane)	290.83	2.40E-01	1.80E-05	3.78
621-64-7	N-Nitrosodi-N-propylamine	130.19	1.30E+04	2.20E-04	1.36
1314-62-1	Vanadium pentoxide	181.88	1.56E+02	na	2.97
1330-20-7	Xylenes (mixtures)	106.17	1.06E+02	2.71E-01	3.12
1336-36-3	Polychlorinated Biphenyls (high risk)	291.99	2.77E-01	1.40E-02	6.29
1336-36-3	Polychlorinated Biphenyls (low risk)	291.99	2.77E-01	1.40E-02	6.29
1336-36-3	Polychlorinated Biphenyls (lowest risk)	291.99	2.77E-01	1.40E-02	6.29
6533-73-9	Thallium carbonate	468.78	5.20E+04	na	-0.86
7429-90-5	Aluminum	30.01	5.94E+04	1.00E+00	0.33
7439-96-5	Manganese	54.94	8.72E+04	1.00E+00	0.23
7439-98-7	Molybdenum	95.94	7.66E+04	1.00E+00	0.23
7440-02-0	Nickel (soluble salts)	58.69	4.22E+05	1.00E+00	-0.57
7440-22-4	Silver	107.87	7.05E+04	1.00E+00	0.23

Table A3. List of Chemicals.

CASRN	Chemical	Molecular Weight (g/mole)	Solubility in Water (mg/L)	Unitless Henry's Law Constant	$Log(K_{OW})$
7440-24-6	Strontium, Stable	87.62	8.04E+04	1.00E+00	0.23
7440-31-5	Tin	120.73	7.91E+03	1.00E+00	1.29
7440-36-0	Antimony	124.78	2.30E+04	1.00E+00	0.73
7440-38-2	Arsenic (inorganic)	77.95	3.47E+04	3.16E+01	0.68
7440-39-3	Barium	137.33	5.48E+04	1.00E+00	0.23
7440-41-7	Beryllium and compounds	9.01	1.49E+05	1.00E+00	-0.57
7440-42-8	Boron and borates only	13.84	4.37E+04	1.00E+00	0.23
7440-43-9	Cadmium	112.41	1.23E+05	1.00E+00	-0.07
7440-48-4	Cobalt	58.93	8.75E+04	1.00E+00	0.23
7440-66-6	Zinc and compounds	67.41	3.44E+05	1.00E+00	-0.47
7487-94-7	Mercuric chloride	271.50	6.90E+04	4.62E-01	-0.22
7664-41-7	Ammonia	17.03	3.74E+03	1.41E-04	-1.38
7723-14-0	Phosphorus, white	34.00	2.05E+05	9.97E-01	-0.27
7782-41-4	Fluorine (soluble fluoride)	38.00	1.69E+00	1.00E+00	0.22
7782-49-2	Selenium and compounds	80.98	8.14E+04	3.98E-01	0.24
8001-35-2	Toxaphene	413.82	5.50E-01	2.45E-04	5.78
14797-55-8	Nitrate	62.00	9.09E+04	1.00E+00	0.21
14797-65-0	Nitrite	47.01	1.20E+05	8.38E-06	0.06
16065-83-1	Chromium (III) (insoluble salts)	na	1.20E+04	na	na
18540-29-9	Chromium (VI) (soluble salts)	na	1.20E+04	na	na
none	Uranium (soluble salts)	na	na	na	na

Notes:
- CASRN = Chemical Abstract Service Reference Number
- The 126 chemicals on this list are found in the RAIS database and either the 410-chemical list (Table B.1) or the 176-chemical lists (Tables 4.4 and 4.7) in PNNL-12040.
- Molecular Weights, Water Solubilities, and Unitless Henry's Law constants are from the EPI Suite software version 3.10.
- Missing values are indicated with "na", which means "not available".

Version 3.10 of the EPI Suite software reports some of the numbers it calculates incorrectly. This shows up in the calculation of the Log Kow values as well as numbers that are calculated from them. It occurs when more than one chemical is found with a similar structure. The software reports the last chemical on the list rather than the chemical that was requested. This error was observed for Dibenz[a,h]anthracene (53-70-3), gamma-Benzene hexachloride (gamma-Lindane) (58-89-9), Dieldrin (60-57-1), cis-1,2-Dichloroethylene (156-59-2), alpha-Benzene hexachloride (alpha-Lindane) (319-84-6), and beta-Benzene hexachloride (beta-Lindane) (319-85-7).

With the exception of the State of Washington's MTCA, the chemicals are not separated into volatile and non-volatile in the calculations presented in the main text. Instead, the appropriate chemical property is used to determine the relative volatility. One such property is the Henry's Law Constant, which is the ratio of the saturated vapor concentration to the aqueous concentration. The unitless Henry's Law Constant (H') may be converted into the units atm per mole/L using the factor RT, where R is the idea gas law constant (0.082057 L-atm/mole-K) and T is the temperature (298.15 K). This is shown in the equation below.

$$K_{HENRY} = H' R T$$

The polychlorinated biphenyls (PCBs) are separated into three categories, high, low, and lowest risk. The first two categories are distinguished by the extent the PCBs have entered the food chain. The high risk PCBs are those that are in the food and may affect children. The low risk PCBs are strictly in water. The lowest risk PCBs are for mixtures containing less than 0.5% of chemicals with more than 4 chlorine atoms.

Many of the organic chemicals on the list in Table A3 decompose in the environment by the action of sunlight, reactions with other chemicals (oxygen especially), heat, and biological action. The decomposition half-lives are not included in the calculations. In effect, it is assumed that the chemicals do not decompose. For inorganic chemicals this is largely true. However, many organic chemicals have measured half-lives that are less than one year. Examples from Table 1 in Jury (1990) are toluene (50 days) and xylene (110 days).

A3.0 HUMAN PARAMETERS

In the various exposure scenarios the data for humans falls into two categories. The first data category is needed to estimate the contaminant intakes. This includes the dietary consumption rates, the breathing rate, duration of external exposures, extent and duration of dermal contact, and the like. The second data category is toxicity of the various hazardous materials. For radionuclides, the measures of toxicity are the internal and external dose factors, and the cancer induction risk coefficients. For chemicals, the measures of toxicity are the hazard index and the cancer induction slope factors. Each of these parameters is discussed in this section.

A3.1 Dietary Consumption Rates

In this section the ingestion rates for all types of produce for all exposure scenarios are presented and compared. In addition, consumption rates for water and trace amounts of soil are given. Finally, garden size is discussed because the assumed garden size controls soil concentration in the garden of the post-intrusion resident.

A3.1.1 Food and Water

A summary of the food and water consumption rates is given in Table A4. Specific food items are listed in the notes to the table. All values are in units of kilograms. The items ingested are separated into three general categories, namely, plants, animal products, and miscellaneous items. Each of these categories has a short list of items that represents related foods. The columns show distinct consumers used in the various exposure scenarios.

Edible plants are grouped in to four types. "Leafy" refers to vegetables whose leafy parts are normally eaten, such as lettuce, cabbage and spinach. "Other" is termed "protected" produce because the edible portion is underground or has some type of non-edible covering. Protected produce includes both fruit and vegetables. Examples are melons, avocados, potatoes, onions, peanuts, tree nuts, artichokes, carrots, garlic, onions, radishes, green peas, chili peppers, and sweet corn. "Fruit" is termed "exposed" produce because airborne contaminants may deposit on the edible portion, but the surface area is small compared to leafy vegetables. Exposed produce includes both fruits and vegetables. Examples of exposed produce are apples, apricots, asparagus, bell peppers, broccoli, Brussels sprouts, cauliflower, celery, cherries, cranberries, cucumbers, eggplant, grapes, peaches, pears, plums, snap beans, squash, strawberries, and tomatoes. "Grains" refers to cereals consumed by humans, such as corn (for meal), oats, soybeans, and wheat. Rice is excluded due to the cooler climate.

For a given element, the protected and exposed categories have very similar model parameters (discussed in Section A5.0), eg., dry-to-wet ratio, crop yield, translocation factor, and root uptake factor. Thus, the issue of whether to include below ground vegetables in the protected or exposed category when dealing with soil contamination is not important. The resulting intakes of radionuclides or toxic chemicals are similar. In effect, there are only three distinct groups of garden produce, namely, leafy vegetables, grains, and everything else.

Edible animal products refer to "Beef", "Milk", "Poultry", and "Eggs". The animal products may be contaminated if the animals ingest contaminated feed and drink. The various animals raised for foods are separated into the two broad categories "Beef" and "Poultry". If the animal resembles a cow (e.g. sheep, goats or pigs), it is "Beef". If the animal resembles a bird (e.g. ducks and turkeys), it is "Poultry". The names simply refer to the most likely animal. “Milk” refers to fresh milk as well as yogurt, ice cream, and condensed milk. In addition, no distinction is made between goat's milk and cow's milk. “Eggs” refers to chicken eggs exclusively.

The miscellaneous category includes “Fish”, “Game”, and “Water”. “Fish” refers to fresh-water fish and shellfish. “Game” refers to wild animals harvested for food, such as deer and waterfowl. “Water” refers to drinking water and beverages made from local water sources.

The column labeled “EPA” comes from an EPA analysis of the 1977-78 USDA Nationwide Food Consumption Survey (Yang and Nelson 1986). The consumption parameters for the "West" region were used in prior Hanford Site disposal facility performance assessments. These consumption rates are averages for all age groups. Game animals were not included. The non-dairy beverage consumption rates measured by the EPA (Yang and Nelson 1986) for the western region are 1.48 liters per day (540 L/y). The grouted waste performance assessment used 1.84 liters per day (672 L/y) (Roseberry and Burmaster 1992). The traditional assumption widely used in other performance assessments is 2 liters per day (730 L/y), which is 35 percent higher than the EPA average and 9 percent higher than the grouted waste PA.

The column labeled “USDA” comes from indirect estimates of average per capita food consumption based on food production in the United States (Putnam and Allshouse, 1999). Losses from exports, industrial uses, and end-of-year stocks were taken into account. The other and fruit consumption rates do not include bananas, pineapples, or citrus fruits, because they are not grown in southeastern Washington. Similarly, the grain consumption rate excludes rice. Game meat was not included in the study. The authors concede “fish consumption is likely understated”. However, the EPA Exposure Factors Handbook (EPA/600-P-95/002Fa) recommends a total fish consumption rate for the general population that is just 11% larger (7.34 kg/y). Beef includes all red meats. When volumes of milk are converted to mass units, a density of 1.03 kg/L is used. Egg consumption is given as 238.7 per person in 1997. To estimate annual consumption rate shown in Table A4, this was rounded to 240, and an average egg weight of 2 ounces (57 g) was assumed.

Comparing the food and water consumption rates from EPA with those from USDA, only fish consumption shows a small decrease. All other food items have larger intake rates. The values for exposed produce (fruit) and poultry show the largest increase. The USDA column will be used to calculate unit dose factors for the post-intrusion resident, the all pathways farmer, and the Columbia River population scenarios. This differs from previous Hanford performance assessments and leads to a small increase in the doses from the food pathway.

The column labeled “HSRAM” gives the food and water consumption rates for adults in the residential and agricultural scenarios found in DOE/RL-91-45 Revision 3, (HSRAM). The consumption parameters listed in that document for the residential and agricultural scenarios are presented in Table A4. The HSRAM gives just two types of garden produce, namely, fruit and vegetables, for the residential and agricultural scenarios. The vegetable consumption rate was separated into leafy and other by keeping the same relative amounts found in the USDA column.

The game consumption rate has been modified from the HSRAM, which lists 1 g/d animal fat. In Paustenbach (1989) the average successful hunter consumes 60 g/d (22 kg/y), which is about half of the total edible portion of one deer. The animal fat is 1.4%, hence, the animal fat consumption rate is 0.84 g/d, which is rounded to 1 g/d in HSRAM. A modifying factor of 0.19 is used to include the hunter success rate, i.e., the fraction of people who hunt that actually obtain a deer. In Table A4 the mass of deer meat is listed rather than animal fat. The hunter success rate factor is included in the value shown (4.2 kg/y).

The fish consumption rate is the HSRAM value of (27 g/d)(365 d/y)=9,900 g/y, which is considerably larger than the values recommended in the Exposure Factors Handbook (EPA/600-P-95/002Fa Section 10), which lists 6.6 g/d fresh water fish, and 20.1 g/d total as the recommended population averages.

The EPA and USDA numbers must be adjusted for the fraction of food grown locally. The HSRAM values already include these adjustments. These fractions are based on the EPA Exposure Factors Handbook (EPA/600/8-89/043). For garden produce 25 percent of the vegetable diet comes from the garden. The other 75 percent is obtained from uncontaminated sources. For animal products, 50 percent of the animal products (including fish) are locally produced and thus contaminated. Note that the updated Exposure Factors Handbook (EPA/600-P-95/002Fa) gives somewhat different values. The 25 percent and 50 percent fractions continue to represent the Exposure Factors Handbook values (see Table 13-71 under Questionnaire Response). The adjusted annual intakes are shown in Table A5.

Table A4. Food and Water Consumptions Rates (kg/y).

	EPA	USDA	HSRAM	NASR
Plants:				
Leafy:	16.4	17.8	5.0	16
Other:	55.6	86.5	24.2	77
Fruit:	38.4	85.8	15.3	76
Grain:	74.0	81.9	0	73
Animal Products:				
Beef:	42.0	50.3	27.4	34
Milk:	104	116	110	226
Poultry:	10.6	29.4	0	20
Eggs:	10.6	13.6	0	9.1
Miscellaneous Items:				
Fish:	6.75	6.58	9.9	197
Game:	0	0	4.2	70
Water:	540	545	730	1,095

Notes:

- The column labeled “EPA” comes from an EPA analysis of the 1977-78 USDA Nationwide Food Consumption Survey (Yang and Nelson 1986). These values are shown for comparison with prior performance assessments.
- The column labeled “USDA” comes from indirect estimates of average per capita food consumption based on food production in the United States (Putnam and Allshouse, 1999). Losses such as from exports, industrial uses, and end-of-year stocks are taken into account. These values are used in the Post-Intrusion Resident and All Pathways Farmer exposure scenarios.
- The column labeled “HSRAM” gives the food and water consumption rates for adults in the recreational, residential, and agricultural scenarios. The water ingestion rate for children is half the value shown. The food consumption rates include adjustment for locally grown fractions.
- The column labeled “NASR” gives the food and water consumption rates for the Native American Subsistent Resident. These are based on the Columbia River Comprehensive Impact Assessment (DOE/RL-96-16). The 70 kg/y in the row labeled “Game” is composed of 22 kg/y deer, 32 kg/y wild birds, and 16 kg/y wild bird eggs.
- “Leafy” = cabbage, lettuce, and spinach
- “Other” = protected produce, namely, avocados, melons, artichokes, beets, carrots, chili peppers, sweet corn, garlic, green peas, lima beans, onions, potatoes, radishes, and tree nuts.
- “Fruit” = exposed produce, namely, apples, apricots, cherries, cranberries, grapes, peaches & nectarines, pears, plums & prunes, strawberries, asparagus, bell peppers, broccoli, brussels sprouts, cauliflower, celery, cucumbers, eggplant, snap beans, and tomatoes.
- “Grain” = wheat, rye, corn, oat, and barley (everything except rice).
- “Beef” = all red meats
- “Milk” = beverage milks, yogurt, fluid cream products, frozen dairy products, condensed & evaporated milk (to convert USDA milk volumes to units of mass, a density of 1.03 kg/L was used)
- “Poultry” = chicken and turkey
- “Eggs” = for the USDA value, the number of eggs consumed (240 per year) is converted to mass units assuming the average mass of an egg is 2 ounces (57 g)
- “Fish” = includes shellfish
- “Water” = includes water added to prepare coffee, tea, soft drinks, beer and distilled sprits, in addition, tap water consumption is assumed to be 25 gallons (95 L) per year.

The column labeled "NASR" gives the food and water consumption rates for the Native American Subsistent Resident (NASR). These are from the Columbia River Comprehensive Impact Assessment (CRCIA) (DOE/RL-96-16 Section 5.1.4.1). Slightly different parameter values are presented in a paper by Harris and Harper (1997). The CRCIA model generally leads to larger intakes and resulting doses or risks. Hence, the CRCIA model is used in this report. The CRCIA gives just one value for consumption of fruit and vegetables (660 g/d). This was separated into the four types shown by keeping the same relative amounts found in the USDA column.

The NASR values for animal protein (150 g/d) and organ meat (54 g/d) shown in Table 5.7 of DOE/RL-96-16 were assumed to include 60 g/d for deer (half of one animal per year). Thus the total consumption rate for beef, poultry, and eggs was taken to be 150+54-60=144 g/d. This was distributed over the beef, poultry, and eggs by keeping the same relative amounts found in the USDA column. The value shown in Table A4 for game is composed of the deer (60 g/d), upland birds and waterfowl (88 g/d), and bird eggs (45 g/d).

The NASR food consumption rates are not adjusted for the fraction locally produced. All of the plant and animal products consumed by the NASR are locally grown. When the EPA and USDA columns are adjusted for the locally grown fractions, the NASR consumption rates are greatest for all food types. Thus, the NASR represents a bounding case.

Table A5. Food and Water Consumptions Rates for the Exposure Scenarios.

Food Consumed (kg/y)	All Pathways Farmer	Native American	Columbia River Population	HSRAM Recreational	HSRAM Residential	HSRAM Agricultural
Leafy	4.45	16	8.9	0	5	5
Other	21.625	77	43.25	0	24.2	24.2
Fruit	21.45	76	42.9	0	15.3	15.3
Grain	0	0	0	0	0	0
Beef	25.15	34	25.15	0	0	27.4
Milk	58	226	58	0	0	110
Poultry	14.7	20	14.7	0	0	0
Eggs	6.8	9.1	6.8	0	0	0
Fish	3.29	197	0.003	9.9	9.9	9.9
Game	0	22	0	4.2	0	4.2
Wild Birds	0	32	0	0	0	0
Wild Eggs	0	16	0	0	0	0
Water	545	1,095	545	14	730	730

Notes:

- The post-intrusion scenarios use the same dietary intakes as shown for the All Pathways Farmer. The Suburban Garden case uses only the vegetable amounts, while the Urban Pasture case uses only the milk amount.
- The HSRAM Industrial worker only consumes 1 L/d of drinking water while at work. The total annual intake is 250 L/y.
- The State of Washington MTCA scenarios use 2 L/d or 730 L/y for water. The fish consumption rate for Method B is 27 g/d (9.9 kg/y), and the fish consumption rate for Method C is 10.8 g/d (3.94 kg/y).

Wild game is not included in Table A5 for the All Pathways Farmer because this is an average individual. Hence, the game intake would be small and contribute very little to the total dose or risk or hazard index. If the average value for the HSRAM Recreational Scenario were used for the All Pathways Farmer, the meat intake would increase by about 17%. Since the wild game is not as contaminated as the cow, the resulting dose from a contaminated deer can be neglected. The consumption of wild game by the population is not included for the same reason. It is a minor addition to the total dose or risk or hazard index.

For exposure of the population along the Columbia River, parameters are scaled up by the assumed total population of 5 million. Two exceptions are water intake and fish consumption. The average drinking rate of 545 L/y per person (Putnam and Allshouse 1999) will be used. About half of this number is water, while the rest is various other beverages, most of which are derived from drinking water supplies. The contaminated fraction of the average diet is assumed to be 50%, due to widespread irrigation. The other 50% is obtained from non-irrigated sources or imported from other regions.

The quantity of contaminated fish consumed by the population along the Columbia River is limited by what the river is able to produce. The total mass of fish harvested from the Columbia River annually and consumed locally is approximately 15 metric tons (PNNL-9823). The average amount of fish consumed by 5 million people is thus 3 grams per year per person.

A3.1.2 Garden Area Determination

From the annual consumption of garden produce it is possible to estimate the minimum garden area needed to supply an individual. This area is required for intruder calculations in which the exhumed waste is spread over a garden.

The quantity of food derived from the garden is proportional to the garden size. To estimate food production per unit garden area, two approaches were considered. The first is commercial food production in Washington State (WA Department of Agriculture 1994). Values for production per acre and per square meter are shown on Table A6. "cwt" means 100 pounds. Bushels of grain were assumed to have a density 70 percent that of water (700 kg/m^3). Thus a bushel of grain is assumed to weigh about 54 lb. The categories used for human consumption are from Table A4. The average person consumes the amount shown, in kg/y. Based on the average food production rate, the necessary garden area is 233 m^2. This total area is mostly needed for production of grains. This area also requires an efficient gardening operation to succeed.

The second approach to estimating garden size uses garden production estimates published by the Washington State University (WSU) Cooperative Extension (1980). Values are listed in Table A7. The referenced document provides estimates of pounds of produce per 10-foot row in a garden. In addition, it gives recommended row spacing. The spacing was treated as the row width to compute production per unit area. The USDA average annual consumption rates from Table A4 were used to determine garden area needs. The WSU production estimates are higher than the commercial production averages hence the needed garden area is smaller (207 m^2). These were assumed to be optimum values under excellent growing conditions.

The post-intrusion resident's garden is assumed to supply vegetables and fruit only. Grains are excluded. Thus, a 100 m^2 garden supplies 100% of the garden produce needs of a single adult over a year's time, or 25% of the garden produce needs of a family of four. Note that this area is half that used in the 2001 ILAW PA (200 m^2) due to the elimination of grains. However, it represents a marked decrease from other Hanford performance assessments, which use a garden area of 2,500 m^2.

The chosen garden area is consistent with recent performance assessments at other DOE sites. The Class L-II disposal facility at the Oak Ridge Reservation has an intruder garden area of 200 m^2 (ORNL-TM/13401). This garden area was judged adequate "to provide half the entire yearly intake of vegetables" (page G-50). A performance assessment for the Nevada Test Site (SAND2001-2977) uses an intruder garden area of 70 m^2 based on food consumption.

Table A6. Commercial Food Production as a Basis for Garden Size.

Type of Produce	Yield per acre	Yield kg/m^2	Garden Area, m^2
Leafy Vegetables	***17.8 kg/y***	***2.35***	***7.6 m^2***
Cabbage			
Chard			
Lettuce	210 cwt	2.35	
Spinach			
Exposed Produce	***85.8 kg/y***	***1.65***	***51.8 m^2***
Apple	17 tons	3.81	
Apricots	6.23 tons	1.40	
Asparagus	35 cwt	0.39	
Broccoli			
Brussel Sprouts			
Bushberries	7,000 lb	0.78	
Cauliflower			
Cherry	6.93 tons	1.55	
Cucumber			
Eggplant			
Grape	10.83 tons	2.43	
Hops	1,884 lb	0.21	
Peach	10 tons	2.24	
Pear	15 tons	3.36	
Plums & Prunes	8.4 tons	1.88	
Rhubarb			
Snap Bean	90 cwt	1.01	
Strawberry	7,000 lb	0.78	
Tomato			
Protected Produce	***86.5 kg/y***	***2.48***	***34.9 m^2***
Bean (dry)	19 cwt	0.21	
Beet			
Carrot	580 cwt	6.50	
Kohlrabi			
Lentils	1340 lb	0.15	
Muskmelon			
Onion	360 cwt	4.04	

Table A6. Commercial Food Production as a Basis for Garden Size.

Type of Produce	Yield per acre	Yield kg/m^2	Garden Area, m^2
Parsnip			
Peas	38 cwt	0.43	
Potato	590 cwt	6.61	
Radishes			
Squash			
Sweet Corn	150 cwt	1.68	
Tree Nuts	0.87 tons	0.20	
Turnip			
Watermelon			
Grains	***81.9 kg/y***	***0.59***	***138.3 m^2***
Barley	67 bu	0.41	
Corn (for meal)	190 bu	1.16	
Oats	68 bu	0.41	
Rye			
Wheat	63.6 bu	0.39	
		Total Garden Area:	**232.6 m^2**

Notes:
- Food production data is from *Washington Agricultural Statistics 1993-1994*.
- Average consumption rates (italics) are from Putnam and Allshouse, 1999.
- A bushel of grain is assumed to have a density 70% of water, so that a bushel weighs 54 lb.

Table A7. Homeowner Food Production as a Basis for Garden Area.

Type of Produce	Yield lb/10 ft	Row Spacing inches	Yield kg/m^2	Garden Area, m^2
Leafy Vegetables	***17.8 kg/y***		***4.48***	***4.0 m^2***
Cabbage	10	24	2.44	
Chard	30	18	9.76	
Lettuce	10	18	3.25	
Spinach	5	12	2.44	
Exposed Produce	***85.8 kg/y***		***2.09***	***41.0 m^2***
Apple		12		
Apricots		12		
Asparagus	5	24	1.22	
Broccoli	10	24	2.44	
Brussel Sprouts	10	24	2.44	
Bushberries		12		
Cauliflower	8	24	1.95	
Cherry		12		
Cucumber	12	24	2.93	
Eggplant	8	36	1.30	
Grape		12		
Hops	0.1	1	0.59	
Peach		12		
Pear		12		
Plums & Prunes		12		

Table A7. Homeowner Food Production as a Basis for Garden Area.

Type of Produce	Yield lb/10 ft	Row Spacing inches	Yield kg/m^2	Garden Area, m^2
Rhubarb	15	36	2.44	
Snap Bean	6	18	1.95	
Strawberry		12		
Tomato	30	48	3.66	
Protected Produce	***86.5 kg/y***		***3.85***	***22.5 m^2***
Bean (dry)		12		
Beet	10	12	4.88	
Carrot	12	12	5.86	
Kohlrabi	7	18	2.28	
Lentils		12		
Muskmelon	30	72	2.44	
Onion	10	12	4.88	
Parsnip	10	18	3.25	
Peas	10	18	3.25	
Potato	20	24	4.88	
Radishes	4	6	3.91	
Squash	25	48	3.05	
Sweet Corn	10	24	2.44	
Tree Nuts		12		
Turnip	20	18	6.51	
Watermelon	40	96	2.44	
Grains	***81.9 kg/y***		***0.59***	***139.8 m^2***
Barley	0.1	1	0.59	
Corn (for meal)	0.1	1	0.59	
Oats	0.1	1	0.59	
Rye	0.1	1	0.59	
Wheat	0.1	1	0.59	
			Total Garden Area:	**207.3 m^2**

Notes:
- Food production data from *Home Gardens*, WSU Cooperative Extension Report EB-422.
- Average consumption rates (italics) are from Putnam and Allshouse, 1999.

A3.1.3 Soil Ingestion

Inadvertent soil ingestion refers to trace amounts associated with soil dust that adheres to hands and is transferred to food or cigarettes. Another route is airborne soil that deposits on the lips and is subsequently ingested. Deliberate soil ingestion is not considered in the calculations, although it may occur in children. A survey of measurements of soil ingestion is presented in NUREG/CR-5512, Section 6.3.2. Soil ingestion is also discussed in detail in the Exposure Factors Handbook, Chapter 4 (EPA/600-P-95/002Fa). Values used in the unit dose and unit risk factors are shown in Table A8.

The average adult is assumed to ingest 100 mg/d in trace amounts. In the Native American scenario, the adult soil ingestion rate is applied to both the irrigated land and shoreline sediment, so that the annual amount ingested is nearly four times greater than the All Pathways

Farmer. In three of the HSRAM exposure scenarios two daily rates are used. The child's soil intake rate is twice the adult's and applies during the first 6 years. The adult rate is used during the next 24 years. For radionuclides, the 30-year total is used to calculate the increased cancer risk from soil ingestion. For non-carcinogenic chemicals, the child's annual intake rate is used for soil ingestion. For carcinogenic chemicals, the 30-year total averaged over 70 years is used for soil ingestion.

In all prior Hanford Performance Assessments, the Post-Intrusion Resident and All Pathways Farmers ingest 36.5 g/y. In the present calculations, the Post-Intrusion cases ingest about half as much, 18 g/y. The reduction is based on the limited time of exposure to the contaminated area (garden, pasture, or field). Note that the Harris and Harper NASR ingests about half as much soil, 36 g/y.

Table A8. Inadvertent Soil Ingestion.

Exposure Scenario	Daily Soil Intake Rate (mg/day)	Exposure Frequency (days/year)	Annual Soil Ingestion (g/year)
Irrigated Land Ingestion Amounts			
Well-Driller	100	5	0.5
Post-Intrusion Scenarios	100	180	18
All Pathways Farmer	100	365	36.5
Native American	200	365	73
Columbia River Population	100	365	36.5
HSRAM Industrial	50	146	7.3
Recreational -- Child/Adult	200 / 100	7	1.4 / 0.7
Residential -- Child/Adult	200 / 100	365	73 / 36.5
Agricultural -- Child/Adult	200 / 100	365	73 / 36.5
Shoreline Sediment Ingestion Amounts			
All Pathways Farmer	100	7	0.7
Native American	200	270	54
Columbia River Population	100	5	0.5
Recreational -- Child/Adult	200 / 100	7	1.4 / 0.7
Residential -- Child/Adult	200 / 100	7	1.4 / 0.7
Agricultural -- Child/Adult	200 / 100	7	1.4 / 0.7

Notes:
- Inadvertent soil ingestion refers to trace amounts ingested after transfer from hands to food or cigarettes.
- Native American values are from DOE/RL-96-16, Revision 1. HSRAM values are from DOE/RL-91-45 Revision 3.
- Two values are given for the last three HSRAM scenarios. The first is the rate for children, and the second is the rate for adults.

A3.2 Inhalation Rates for People

To determine the internal dose or risk from the inhalation of vapors and suspended particulate matter, one must compute the total activity inhaled. Values for the average air concentration, the time exposed at that concentration, and the average breathing rate during the exposure period are presented in this section. The inhalation intakes are separated into those from contaminated soil and those from contaminated water.

A3.2.1 Airborne Soil

A mass loading approach is used to estimate airborne concentrations of radionuclides for scenarios involving resuspension of contaminated soil. For the intrusion scenarios, a basic assumption regarding the waste materials in the soil is that the particle size distribution of the waste (either as exhumed waste or as contaminated irrigation water) is similar to that of the soil. If waste particles were finer than soil particles, then soil that becomes airborne would have a higher concentration of waste than the average for the garden. If waste particles were coarser than soil particles, then the airborne soil would be deficient in waste. For the irrigation scenarios, the dissolved and suspended particulate will most likely attach to the finer soil particles because that is where the greatest surface area is found.

The average mass loading in air depends on what is happening to the contaminated soil. Active gardening produces the largest average mass loading, at 0.5 mg/m^3. Routine activities outdoors are assumed to take place at an average air concentration of 0.1 mg/m^3. Indoor activities are assumed to take place at lower air concentrations due to the presence of other airborne particulate sources. The basis for these air concentrations is presented very effectively in NUREG/CR-5512, Section 6.3.1. It should be noted that the fine particulate suspended in air may have a greater contaminant concentration than the soil from which it is obtained. Hence, the mass loadings that have been chosen are somewhat high. (Typical annual average airborne mass loadings observed outdoors at the Hanford Site are about 0.03 mg/m^3.)

In the well-drilling scenario, the individual is assumed to be exposed for 40 hours, spread over 5 days. This is the time needed to drill the well. During this time the individual breathes at the outdoor activity rate (1.21 m^3/h) defined in ICRP Publication 66 (1994), *Human Respiratory Tract Model for Radiological Protection*. The actual inhalation scenario is highly variable. The worker can be exposed to a high concentration when the waste material comes out of the hole. However, this material is soon buried by clean material coming from farther down the hole. In addition, the material is likely wetted as part of the drilling operation and to minimize fugitive dust emissions. Another modeling approach is to average the contamination over the assumed spreading area and compute the total inhaled over the 40 hour work period.

In the Grouted Waste performance assessment (WHC-SD-WM-EE-004) the well-drilling worker inhales resuspended dust at a concentration of 0.1 mg/m^3 for one hour. The breathing rate (1.20 m^3/h) is from ICRP Publication 23, *Report of the Task Group on Reference Man* (1975). However, the air concentration was not based on the waste concentration, but rather on the average soil concentration after spreading. In effect, the 0.64 m^3 of waste exhumed in the Grouted Waste PA was diluted to a total volume of 15 m^3=(100 m^2)(0.15 m). These assumptions lead to the inhalation of 0.12 mg soil containing 0.0051 mg of waste, as shown in the calculations below. Note that the soil density in the well is assumed to be the same as the soil density of the tailings to simplify the comparison with the prior performance assessments.

$$\text{Soil Inhaled (Grout PA)} = (1\ \text{h})(1.2\ \text{m}^3/\text{h})(0.1\ \text{mg/m}^3) = 0.12\ \text{mg soil inhaled}$$

$$\text{Waste Inhalaed (Grout PA)} = (0.12\ \text{mg soil})\left(\frac{0.64\ \text{m}^3\ \text{grout}}{15\ \text{m}^3\ \text{soil}}\right)$$
$$= 0.0051\ \text{mg grout inhaled}$$

In the 2001 ILAW PA (DOE/ORP-2000-24 Revision 0) the driller inhales suspended soil for a period of 40 hours. The airborne soil is diluted to the average concentration of the well tailings (80 m well depth assumed) in addition to the dilution that results when the exhumed material is spread over an area of 100 m^2 to a depth of 0.15 m. Finally, the 2001 ILAW PA assumes that 1% of the exhumed waste is available for inhalation. The inhalation intakes are shown below.

$$\text{Soil Inhaled (ILAW PA)} = (40\ \text{h})(1.2\ \text{m}^3/\text{h})(0.1\ \text{mg/m}^3) = 4.8\ \text{mg soil inhaled}$$

$$\text{Waste Inhalaed (ILAW PA)} = (4.8\ \text{mg soil})\left(\frac{0.272\ \text{m}^3\ \text{waste}}{5.84\ \text{m}^3\ \text{borehole}}\right)\left(\frac{0.272\ \text{m}^3\ \text{waste}}{15\ \text{m}^3\ \text{soil}}\right)(0.01)$$
$$= 0.000041\ \text{mg waste inhaled}$$

In the present report, the dilution of the well tailings to a volume of 15 m^3 is eliminated. The driller inhales 4.84 mg of the average soil concentration taken from the well. The well depth is 100 m and the waste depth is assumed to be 8 m. If 10% of the exhumed waste is available for inhalation, then the resulting inhalation intake is shown below.

$$\text{Soil Inhaled (Tank Waste PA)} = (40\ \text{h})(1.21\ \text{m}^3/\text{h})(0.1\ \text{mg/m}^3) = 4.84\ \text{mg soil inhaled}$$

$$\text{Waste Inhalaed (Tank Waste PA)} = (4.84\ \text{mg soil})\left(\frac{8\ \text{m waste}}{100\ \text{m well}}\right)(0.1)$$
$$= 0.039\ \text{mg waste inhaled}$$

For estimating inhalation exposure in the post-drilling residential scenario, the individual spends the entire year living in the contaminated area. The Grouted Waste performance assessment (WHC-SD-WM-EE-004) used an average inhalation rate of 8,520 m^3 per year and an average air concentration of 0.1 mg/m^3. The annual amount of soil inhaled was 852 mg. The 200 West Area Burial Ground performance assessment (WHC-EP-0645) used more detailed inhalation assumptions based on PNNL-6312. The inhalation dose was based on an annual inhalation of 445 milligrams.

Inhalation dose for the tank waste PA is an update of the model for the 2001 ILAW PA (DOE/ORP-2000-24 Revision 0). It is a refinement of the model used for the 200 West Area Burial Ground (WHC-EP-0645). It is also very similar to the method discussed in NUREG/CR-5512. The post-intrusion residents spend a portion of the day in various average air concentrations. These are shown in Table A9 for all three of the post-intrusion residents as well as the all pathways farmer (irrigation scenario). The breathing rates shown on Table A9 are from ICRP Publication 66 Table B.16B. In Table A9 the 3,102 hour period asleep is 8.5 hours per day (ICRP 66), 365 days per year. The exposed individual is outdoors for a certain number of hours each day for 180 days in every case.

The suburban resident with a garden spends 2 h/d (360 h/y) in or near his garden. Of this, about 10 hours are spent in relatively dusty conditions. Due to the small size of the garden (100 m^2), it is assumed that the average air concentration during the non-outdoor periods is 10% of the air quality standard, (0.10)(0.050 mg/m^3)=0.005 mg/m^3. This is the concentration of contaminated soil in the air breathed by the resident. There are other (i.e., uncontaminated) sources for airborne particulate. The annual soil mass inhaled by the suburban gardener is 87 mg/y, as shown in Table A9.

The rural resident with a cow spends 4 h/d (720 h/y) in or near his pasture and hay field. Of this, about 10 hours are spent in relatively dusty conditions. Due to the size of the pasture and hay field (5,000 m^2), it is assumed that the average air concentration during the non-outdoor periods is 20% of the air quality standard. The larger value is based on the larger area of the pasture and hay field. The annual soil mass inhaled by the rural cow owner is 169 mg/y, as shown in Table A9.

The commercial farmer spends 8 h/d (1,440 h/y) in or near his fields. Of this, about 10 hours are spent in relatively dusty conditions. Due to the size of the field (160 acre, or 647,500 m^2), it is assumed that the average air concentration during the non-outdoor periods is 20% of the air quality standard. The larger value is based on the larger area of the pasture and hay field. The annual soil mass inhaled by the rural cow owner is 169 mg/y, as shown in Table A9.

The all pathways farmer spends a portion of his time in various average air concentrations. These are shown in Table A9. For 180 days the individual is outdoors. The all pathways farmer spends 10 h/d (1800 h/y) exposed to higher levels of dust outdoors. Of this, about 100 hours are spent in relatively dusty conditions. In Table A9 the 3,102 hour period asleep is 8.5 hours per day (ICRP 66), 365 days per year. Due to the small size of the garden, it is assumed that the average air concentration during the non-outdoor periods is at the air quality standard as shown in Table A9. The annual soil mass inhaled by the all pathways farmer is 539 mg.

The outdoor air concentrations used in the table are discussed at length in NUREG/CR-5512, Section 6.3.1. The values chosen represent conservative bounds on likely concentrations for the activities indicated. The exposure times are also based on the NUREG/CR-5512, although the document is not as explicit as to the assumptions behind the time periods used. It appears that NUREG/CR-5512 includes a vacation period of 2 weeks away from the residence. This is a minor (3%) reduction in the mass inhaled, and is not included. The combinations shown on Table A9 for the post-intrusion resident and all pathways farmer scenarios lead to the annual inhalation amounts shown. Dividing these by the volume of air inhaled in a year (8,094 m^3) gives the average concentrations shown in the table subheadings.

Table A9. Calculation of the Soil Inhalation Amounts.

Activity	Air Concentration (mg/m^3)	Exposure Time (hours/year)	Breathing Rate (m^3/hour)	Mass Inhaled (mg/year)
Post-Intrusion Resident -- Suburban Garden (Annual Average is 0.0107 mg/m^3)				
Asleep	0.005	3,102	0.45	7.0
Indoors	0.005	5,298	1.18	31.3
Outdoor	0.1	350	1.21	42.4
Gardening	0.5	10	1.21	6.1
Away		0		0.0
	Total Time:	8,760	***Soil Inhaled:***	***87***
Post-Intrusion Resident -- Rural Pasture (Annual Average is 0.0209 mg/m^3)				
Asleep	0.01	3,102	0.45	14.0
Indoors	0.01	4,938	1.18	58.3
Outdoor	0.1	700	1.21	84.7
Gardening	0.5	20	1.21	12.1
Away		0		0.0
	Total Time:	8,760	***Soil Inhaled:***	***169***
Post-Intrusion Resident -- Commercial Farm (Annual Average is 0.0397 mg/m^3)				
Asleep	0.02	3,102	0.45	27.9
Indoors	0.02	4,218	1.18	99.5
Outdoor	0.1	1,400	1.21	169.4
Gardening	0.5	40	1.21	24.2
Away		0		0.0
	Total Time:	8,760	***Soil Inhaled:***	***321***
All Pathways Farmer (Annual Average is 0.0666 mg/m^3)				
Asleep	0.05	3,102	0.45	69.8
Indoors	0.05	3,858	1.18	227.6
Outdoor	0.1	1,750	1.21	211.8
Gardening	0.5	50	1.21	30.3
Away		0		0.0
	Total Time:	8,760	***Soil Inhaled:***	***539***

Notes:

- Air concentrations for the All Pathways Farmer are from NUREG/CR-5512, Section 6.3.1. The reduced values for the post-intrusion scenarios depend on the affected area.
- Each individual spends 8.5 hours per day, 365 days per year asleep. For 180 days the post-intrusion resident spends 2, 4, or 8 h/d outdoors, while the all pathways farmer spends 10 h/d outdoors.
- Breathing rates are from ICRP 66 (1994).
- The All Pathways Farmer is exposed to the more ubiquitous soil contamination resulting from a contaminated water supply. Hence, the air concentration is at the ambient air quality guideline. The Post-intrusion Resident is exposed less frequently. Hence, the air concentration is smaller by a factor of 10.

If the intakes are averaged over one year, and the annual average breathing rate from ICRP 66 (8,094 m^3/y) is applied to calculate the amount inhaled, then the average air concentration for the all pathways farmer is 0.0666 mg/m^3 and the average air concentration for the post-intrusion resident is 0.0158 mg/m^3. These are shown on Table A10.

The Native American inhales at the much higher rate from DOE/RL-96-16, 30 m^3/d at an average concentration of 0.1 mg/m^3 (DOE/RL-96-16 Table 5.7). Thus the annual intake is 1,095 mg soil. As with the food pathways, this is greater than the all-pathways farmer. The inhalation intakes of resuspended soil are summarized in Table A10.

The Columbia River population average is based on an exposure of 12 hours per day to a mass loading of 0.05 mg/m^3 at the daily average breathing rate. This leads to an annual inhalation of 405 milligrams of soil, as shown below. This is nearly the same intake as used in the 2001 ILAW PA (416 mg/y). In the 200 West Area Burial Ground PA (WHC-EP-0645) the annual inhalation was twice as great. This is unrealistically high, since the air concentration of contaminated material (0.1 mg/m^3) is a bounding value. In addition, there are other sources of airborne material that are not contaminated. Hence the estimate shown below will be used for population dose.

$$(8{,}094\ m^3/y)(0.05\ mg/m^3) = 405\ mg/y$$

Table A10. Inhalation of Contaminated Soil.

Exposure Scenario	Breathing Rate (m^3/day)	Average Air Concentration (mg/m^3)	Exposure Frequency (days/year)	Annual Soil Inhalation (mg/y)
Well-Driller	9.68	0.1	5	4.84
Post-Intrusion Suburban Resident	22.175	0.0107	365	87
Post-Intrusion Rural Resident	22.175	0.0209	365	169
Post-Intrusion Commercial Farm	22.175	0.0397	365	321
All Pathways Farmer	22.175	0.0666	365	539
Native American	30	0.1	365	1,095
Columbia River Population	22.175	0.05	365	405
HSRAM Industrial	20	0.05	250	250
Recreational -- Child/Adult	10 / 20	0.05	7	3.5 / 7
Residential -- Child/Adult	10 / 20	0.05	365	182.5 / 365
Agricultural -- Child/Adult	10 / 20	0.05	365	182.5 / 365

Notes:
- Breathing rates for the Well Driller and the All Pathways Farmer are from Table B.16B of ICRP 66 for the adult mail sedentary worker. Breathing rate for the Native American comes from DOE/RL-96-16. Breathing rates for the HSRAM scenarios are from the HSRAM. Two values are given for the last three HSRAM scenarios. In these scenarios, non-carcinogens are inhaled at the child's rate (10 m^3/d), while carcinogens are inhaled at the adult's (20 m^3/d).
- The Average Air Concentrations for the post-intrusion residents and the all pathways farmer are from Table A9.
- The annual soil inhalation is calculated as the product of the breathing rate, the air concentration and the exposure frequency.

In the HSRAM scenarios, the average air concentration is the national ambient air quality standard, 0.05 mg/m^3. The daily inhalation rate is either 10 m^3/d or 20 m^3/d. The smaller number is the breathing rate for children. The intake of non-carcinogens is evaluated using the child's inhalation rate (10 m^3/d). The inhalation of carcinogens is modeled at the adult inhalation rate (20 m^3/d). In the industrial scenario there are no children, so the larger breathing rate is used for all materials. In the industrial scenario, the annual inhalation time is 250 days so that the total annual inhalation is 250 mg soil. In the recreational scenario the annual inhalation time is

7 days, so the total annual inhalation is 3.5 mg soil for non-carcinogens and 7.0 mg soil for carcinogens. In the residential and agricultural scenarios the annual inhalation time is 365 days so that the total annual inhalation is 182.5 mg soil for non-carcinogens and 365 mg soil for carcinogens. The HSRAM inhalation intakes are therefore lower than the residential gardener commonly used in Hanford Site performance assessments.

Special Model for Tritium

Airborne concentrations of tritium in the irrigation scenarios are based on airborne water described in the next section. The contribution from the soil is included in the airborne water, and is not calculated separately. Airborne concentrations of tritium for the post-intrusion scenarios are calculated using an evaporation model derived from the RESRAD manual (ANL/EAD/LD-2). The simple box model used for the tank waste PA assumes there is a volume of air directly over the garden that has a tritium concentration fed by evaporation and diminished by movement of air through the volume. The air volume is the garden area times a vertical height selected to represent the average extent of contamination. The rapid turnover of water during the irrigation season means that all of the tritium has left the soil in a few weeks. The rate at which the tritium leaves the surface soil layer decreases with time due to leaching, evaporation, and radioactive decay. The evaporation rate is the amount currently in the garden times the evaporation constant (λ_E). The leaching and evaporation are discussed in Section A6.0. The time dependence of the airborne tritium in the volume of interest is shown in the equations below.

$$\text{Tritium evaporation from garden} = \lambda_E \, Q_0 \, e^{-\lambda_T t}$$

$$\lambda_E = \frac{E}{\theta \, L \, T_{irr}} \quad \text{and} \quad \lambda_T = \frac{P + I}{\theta \, L \, T_{irr}} + \lambda_R$$

$$\text{Wind removal from box} = U \, H \sqrt{A} \, C_A = \mu \, W$$

$$C_A = \frac{W}{A \, H} \quad \text{and} \quad \mu = \frac{U}{\sqrt{A}}$$

$$\frac{dW}{dt} = \lambda_E \, Q_0 \, e^{-\lambda_T t} - \mu \, W$$

where

A	=	surface area of the garden, 100 m^2
C_A	=	tritium air concentration in the volume (AH) above the garden, in Ci/m^3
D	=	thickness of the surface soil layer from which nuclides migrate, 0.15 m (5.9 inches).
E	=	total evapo-transpiration during the irrigation season, 0.7806 m from Section A6.0
H	=	effective vertical height above the garden for estimating air concentrations from Table A11a
I	=	total irrigation water applied during the irrigation season, in 0.823 m Nearly all of this is deposited during the 6 month period from April to September.
P	=	total precipitation, in centimeters, during the irrigation period. Over the period 1971 to 2000, the precipitation during the 6 month irrigation season (April to September) has been 0.05766 m (PNNL-13859).
Q_0	=	initial total tritium activity in the garden, in Ci

t = elapsed time, in years. At t=0 the well was drilled and spread in the garden and irrigation begins.
T_{irr} = irrigation period, 0.5 y
U = harmonic wind speed average through the volume of interest, 2.05 m/s from PNNL-13859 for the years 1955 to 2001
W = amount of tritium in the volume of air, Ci
λ_E = surface soil layer removal constant for removal by evaporation during the irrigation season, 52.04 per year
λ_R = radioactive decay constant for tritium, 0.05622 per year
λ_T = total tritium removal constant during the irrigation season, 58.76 per year
μ = effective removal constant by wind moving through a volume of air over the contaminated area. Calculated values are shown in Table A11a
θ = volumetric water content of the surface soil, milliliters of water per cubic centimeter of soil. A value of 0.2 ml/cc is assumed (Section A6.0).

The solution for the activity in the volume of interest (W) is shown below. The total activity inhaled by the resident is the time integral of the air concentration over the irrigation season. Because the removal constants are large, this is effectively an integral from 0 to infinity. The equation for the activity of tritium inhaled by the post-intrusion resident is shown below.

$$W = \frac{\lambda_E\, Q_0}{\lambda_T - \mu}\left(e^{-\mu t} - e^{-\lambda_T t}\right)$$

$$\text{Tritium Inhaled} = \frac{\lambda_E\, Q_0\, F_{PI}\, BR}{A\, H\, \mu\, \lambda_T} = \frac{\lambda_E\, Q_0\, F_{PI}\, BR}{\sqrt{A}\, H\, U\, \lambda_T}$$

where

A = surface area of the garden, 100 m^2
BR = breathing rate for the post-intrusion resident when outdoors in his garden, 1.21 m^3/h from ICRP 66
F_{PI} = fraction of air that the individual breathes while located in the contaminated area. Computed as the volume of air inhaled during the hours outdoors divided by the volume inhaled in 1 day. For the suburban gardener this is (2 h)(1.21 m^3/h)/(22.175 m^3) = 0.109
H = effective vertical height above the garden for estimating air concentrations, as shown in Table A11a
Q_0 = initial total tritium activity in the garden, in Ci
t = elapsed time, in years. At t=0 the well was drilled and spread in the garden and irrigation begins.
U = harmonic wind speed average through the volume of interest, 2.05 m/s from PNNL-13859 for the years 1955 to 2001
W = amount of tritium in the volume of air, Ci
λ_E = evaporation constant during the irrigation season, 52.04 per year
λ_T = total tritium removal constant during the irrigation season, 58.76 per year
μ = effective removal constant by wind moving through a volume of air over the contaminated area. Calculated values are shown in Table A11a

Input assumptions and calculated results are shown in the table below. The last column shows the fraction of tritium exhumed that is inhaled by the exposed individuals. This fraction is used to calculate the soil inhalation dose from tritium for the post intrusion scenarios.

Table A11a. Calculation of Tritium Inhaled from Soil Contamination.

Post-Intrusion Scenario	Time Exposed (h/d)	Inhaled Air Fraction, F_{PI}	Averaging Area (m^2)	Wind Loss Rate, μ (per h)	Effective Mixing Height (m)	Tritium Inhalation Fraction
Suburban Garden	2	0.1091	100	737.9	1	1.585E-06
Rural Pasture	4	0.2183	5,000	104.4	2	2.241E-07
Commercial Farm	8	0.4365	647,500	9.170	4	1.970E-08

The harmonic average wind speed is the inverse of the average of the inverse wind speeds from PNNL-13859 for the years 1955 to 2001. The inverse speeds are weighted by the fraction of the hourly readings that have wind speeds in that group. The calm group in PNNL-13859 is assumed to have a wind speed of 1 mile/hour. During the year, the average wind speed is slightly greater during the summer months, but this has a small effect on the average speed.

The atmospheric dispersion parameter used in the EPA Soil Screening Guidance documents (EPA/540/R-96/018 and EPA/540/R95/128) to relate the surface emission rate (g/m^2 per second) to the average air concentration at the ground surface (kg/m^3) is known as Q/C. It is calculated using the EPA software ISCST3 (EPA-454/B-95-003) for area sources. The value given in the soil screening guidance is 68.81 g/m^2 per second per kg/m^3 calculated using Los Angeles wind data and a 0.5-acre-square source. (0.5 acre = 2,023 m^2). It is an annual average value at an elevation of zero meters above the soil surface. In the formalism shown above for tritium, the quantity Q/C is defined as shown below for the suburban garden. For the rural pasture (i.e. H = 2 m and A = 5,000 m^2) the Q/C is 58.0 g/m^2 per second per kg/m^3.

$$Q/C = \frac{H\,U}{\sqrt{A}} = \frac{(1\,\text{m})(2.05\,\text{m/s})}{\sqrt{100\,\text{m}^2}} = 0.205\,\text{m/s} = 205\,\frac{\text{g}}{\text{m}^2\,\text{s}}\ \text{per}\ \frac{\text{kg}}{\text{m}^3}$$

The effective Q/C value used in this report leads to smaller amounts of tritium inhaled than using the value presented in the EPA soil screening guidance documents. The value chosen can be regarded as an approximation of the result for an elevation greater than zero meters above the contaminated soil. Table A11b summarizes some ISCST results using Hanford Site wind data collected at the 200 East area tower for the years 1992 to 1996. Air concentrations were calculated for a unit release rate for two contaminated areas at various radial distances and elevations. The peak values are shown in the table below. An example input file is shown in the first attachment.

The Hanford Site-specific result for the Q/C parameter shown in Table A11b is somewhat smaller than the EPA default value of 68.81 g/m^2 per second per kg/m^3. However, the numbers from the box model use a more realistic assumption of non-zero receptor elevation. The values for the suburban garden, rural pasture, and commercial farm for tritium inhalation are 205, 58.0, and 10.2 g/m^2 per second per kg/m^3, respectively.

Table A11b. Values for Q/C from ISCST3.

Source Area	Receptor Elevation (m)	Peak Radial Distance from Source Center (m)	Air Concentration from ISCST3 (g/m^3)	Q/C (g/m^2-s per kg/m^3)
100 m^2	0	1.5	9.235	108.3
Suburban	0.5	8	1.200	833.2
Garden	1	15	0.3712	2,694
1/2 Acre	0	8	19.49	51.30
(2,023 m^2)	0.5	8	7.473	133.8
EPA Standard	1	14	3.298	303.3
5,000 m^2	0	12	23.093	43.30
Rural Pasture	0.5	12	10.783	92.74
	1	15	5.824	171.7

Notes:

- The source area is square with an emission rate of 1 g/m^2 per second.
- Hanford Site wind data from the 200 East Area for the years 1992 to 1996 was used.
- The quantity Q/C is calculated as 1000 divided by the ISCST3 results.

A3.2.2 Airborne Water

For scenarios with inhalation of radionuclides suspended in water, three situations are modeled. The first is inhalation of airborne contaminants from ambient sources such as overhead irrigation, wind blowing across puddles, drops falling off foliage, and indoor sources such as washing and cooking. The second is inhalation of spray during a shower. The third is inhalation of contaminants in water that flashes to steam in a wet sauna or "sweat lodge". These moisture inhalation pathways were used in the 2001 ILAW PA, but not in prior Hanford performance assessments.

Because tritium is modeled as water (HTO), an equilibrium approach is used for tritium. The ratio of airborne tritium to total water in the air is the same as the concentration of the tritium in the water. For other radionuclides, air concentrations are estimated using entrainment factors suitable for the processes that aerosolize the liquid. For chemicals the air concentration is estimated using Henry's Law. To be consistent with the NASR in DOE/RL-96-16, the waterborne air concentration in the sweat lodge is set to 0.1 L/m^3, which means each cubic meter of air inhaled contains the contaminants found in 0.1 L of water.

The entrainment of dissolved materials into the air requires some physical process, such as a water spray during irrigation or showering, to create droplets that will remain airborne for a time. While these droplets are airborne they evaporate and leave behind any suspended solids as airborne particles. The air concentration of the dissolved materials is therefore proportional to the total water content of the air. The constant of proportionality is assumed to be the entrainment factor. There are other sources of humidity that involve no entrainment. Neglecting these lends conservatism to the air concentration estimates.

A bounding water droplet concentration in air is about 10 mg liquid/m^3, a value characteristic of fogs (Hinds 1982). This fog will be included in the shower, but not the ambient case. The evaporation of the water droplets leads to partially saturated water vapor (a gas) in the shower. The assumed temperature and relative humidity determines the bounding water vapor concentration. Having determined the water content of the air, the next step is to select appropriate entrainment factors.

In *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities, Volume 1* (DOE-HDBK-3010-94) data for aqueous solutions under various conditions are presented. The ambient condition is treated as a free-fall spill of liquid, for which the respirable release fraction shown on page 3-4 is 0.0002. The sudden depressurization of superheated aqueous solutions is summarized on page 3-4 also. The recommended bounding value (0.1) could be used to represent the sweat lodge, in which water flashes to steam when poured on hot rocks. The bounding value for lower temperature superheated water being suddenly depressurized (0.01) will be used to represent the shower. These values are shown in Table A12.

In Table A12, the ambient contribution to water inhaled is divided into the irrigation months (April through September) and the non-irrigation months (October through March). Because the irrigation season is largely outdoor activity, Hanford Site averages from PNNL-13859 are used for the average temperature (19.46 C) and the average relative humidity (40.2%). At this temperature and humidity the water vapor concentration is 0.89% or 6.7 g/m^3. The conversion of vapor concentration from mole fraction to mass concentration uses the formula weight for water (18.0153 g/gmole) and the ideal gas law, as shown below. Note that the temperature is in degrees Kelvin rather than Celsius, and also that Table A12 uses cubic meters (m^3) as the unit for volume rather than liters.

Mass of water vapor per unit volume =
(18.0153 g/gmole)(Vapor Mole Fraction)/(0.082057 L·atm/gmole/°K)/(Temperature)

During the non-irrigation season, time indoors is increased, so average indoor temperature (20 C) and humidity (30%) is used in the calculation of waterborne air concentration. A small amount of dilution by uncontaminated water sources brought into the home is assumed (90%).

The entrainment factors described above are next applied to the airborne water content to calculate the equivalent concentration of dissolved particulate that is airborne. The airborne concentration of entrained contaminants is shown in Table A12 in the line below the entrainment factors. The units of g/m^3 should be interpreted as the mass of contaminated water (i.e., ground water or Columbia River water) that is present in each cubic meter of air. The mass airborne can be converted to volume airborne using an assumed density for dilute aqueous solutions of 1,000 g/L.

The total concentration of the contaminated water in air is the sum of the "Entrained Contaminants" and "Droplet Concentration". For ambient conditions an additional factor corrects for the presence of uncontaminated sources of moisture. This is the line labeled "Dilution Factor". As discussed in Section A6.2, this leads to a factor of 93.5% during the irrigation season. During the remainder of the year (without irrigation) the airborne water contamination is based on approximate indoor conditions.

The “Total Contaminant Airborne” is the product of the rainfall “Dilution Factor” and the sum of the “Entrained Contaminant” and the “Droplet Concentration”. For tritium, the “Tritium Airborne” is the product of the rainfall “Dilution Factor” and the sum of the “Water Vapor Concentration” and the “Droplet Concentration”.

The annual intakes in the various exposure scenarios are calculated using the air concentrations from Table A12 and the breathing rates and annual exposure times shown in Table A13. The volume of liquid inhaled during the year is the product of these three factors. The assumed density of the irrigation water is 1.0 kg/L.

Table A12. Water Concentration in Air.

Parameter	Ambient April - September	Ambient October - March	Shower
Air Temperature, C	19.46	20	40
Air Temperature, F	67.03	68	104
Air Temperature, K	292.61	293.15	313.15
Relative Humidity	40.2%	30%	80%
Water Vapor Concentration	0.89%	0.69%	5.82%
Water Vapor Concentration	6.7 g/m^3	5.1 g/m^3	40.8 g/m^3
Entrainment Factor	0.0002	0.0002	0.01
Entrained Contaminant	***0.00134 g/m^3***	***0.00102 g/m^3***	***0.408 g/m^3***
Droplet Concentration	***0***	***0***	***0.01 g/m^3***
Dilution Factor	93.5%	90%	100%
Total Contaminant Airborne	0.00125 g/m^3	0.00092 g/m^3	0.418 g/m^3
Tritium Airborne	6.26 g/m^3	4.59 g/m^3	40.8 g/m^3

Notes:

- The first column of ambient conditions uses air temperature, relative humidity, and rainfall dilution from Hanford meteorological data (PNNL-13859). The second column uses reasonable assumptions based on indoor conditions. The two are similar in magnitude.
- Water Vapor Concentration is given as both a mole fraction and mass concentration.
- The Entrainment Factors are based on particulate releases measured during violent boiling of solutions in DOE-HDBK-3010-94.
- The shower temperature is based on typical hot water settings. The relative humidity during the shower is a value selected from the likely range of 60% to 100%.
- The airborne concentrations are the effective mass of solution per cubic meter of air.

The All Pathways Farmer takes a shower every day that lasts 15 minutes. Since the indoor activity breathing rate is 1.18 m^3/h, the volume of air inhaled during the shower is 0.295 m^3. This volume has been subtracted from the daily air volume inhaled (22.175 m^3) because the air concentrations during the shower include the effect of ambient conditions. Hence, the ambient daily volume inhaled is 21.88 m^3. The resulting annual inhalation of 0.054 L (48 L tritium) is similar to the intakes used in the 2001 ILAW PA, namely, 0.084 L (43.5 L tritium).

The Native American Sweat Lodge, or wet sauna, uses parameters listed in DOE/RL-96-16 (CRCIA). The Native American spends 1 hour in the sweat lodge every day. The NASR breathing rate during this activity is the daily average, 30 m^3/d divided by 24 h/d, or 1.25 m^3/h. The daily total is not adjusted for the hour spent in the sweat lodge. The resulting annual inhalation of 46 L (105 L tritium) is larger than the intakes used in the 2001 ILAW PA, namely, 0.179 L (53 L tritium). The present NASR model is more consistent with the CRCIA.

Table A13. Water Inhalation of Radionuclides by Scenario.

Exposure Scenario	Daily Volume Inhaled (m^3/day)	Air Concentration (g/m^3)		Exposure Frequency (days/year)	Annual Inhalation (L/year)	
		Other	Tritium		Other	Tritium
All Pathways Farmer				***Total***	*0.054*	*48*
Ambient	21.88	0.001085	5.43	365	0.009	43.4
Shower	0.295	0.418	40.8	365	0.045	4.4
Native American				***Total***	*46*	*105*
Ambient	30	0.001085	5.43	365	0.012	59.5
Sweat Lodge	1.25	100	100	365	45.6	45.6
Columbia River Population				***Total***	*0.039*	*46*
Ambient	21.98	0.001085	5.43	365	0.009	43.6
Shower	0.197	0.418	40.8	365	0.030	2.9
HSRAM Industrial				***Total***	*0.026*	*29*
Ambient	20	0.001085	5.43	250	0.005	27
Shower	0.197	0.418	40.8	250	0.021	2.0
HSRAM Recreational				***Total***	***0.00058***	***0.056***
Ambient	0	0.001085	5.43	7	0	0
Shower	0.197	0.418	40.8	7	0.00058	0.056
HSRAM Residential				***Total***	*0.036*	*33*
Ambient	15	0.001085	5.43	365	0.006	29.7
Shower	0.197	0.418	40.8	365	0.030	2.9
HSRAM Agricultural				***Total***	*0.036*	*33*
Ambient	15	0.001085	5.43	365	0.006	29.7
Shower	0.197	0.418	40.8	365	0.030	2.9

Notes:

- The ambient breathing rates for the non-HSRAM scenarios have been reduced to remove the breathing that takes place during the shower. No adjustment is made for the NASR. In the HSRAM residential and agricultural scenarios, the average indoor breathing rate (15 m^3/d) is used.
- The All Pathways Farmer showers 15 minutes per day. The Columbia River Population and HSRAM individuals shower 10 minutes per day. The sweat lodge lasts 1 hour and occurs every other day.
- The annual intakes for the child in the Recreational scenario are half the values shown.
- The air concentration for the NASR Sweat Lodge is from DOE/RL-96-16. The other air concentrations are calculated in Table A10. The ambient concentration is the average of the two shown in Table A10.
- The annual inhalation is the equivalent volume of water that is inhaled each year. It is calculated as the product of the breathing rate, the air concentration, and the exposure frequency.

Note that the Harris and Harper (1997) model for the NASR uses a higher air concentration in the sweat lodge, 164 g/m^3. However, this concentration is breathed at a slower rate, which results in a minor increase in the total inhaled during the year, 50 L/y.

The Columbia River Population is assumed to take 10-minute showers every day of the year. Since the indoor breathing rate is 1.18 m^3/h (ICRP 66), the volume of air inhaled during the shower is 0.197 m^3. This volume has been subtracted from the daily air volume inhaled because the air concentrations during the shower include the effect of ambient conditions.

Hence, the ambient daily volume inhaled is 21.978 m^3 rather than 22.175 m^3. The resulting annual intake shown in Table A13 (0.039 L, 46 L tritium) is similar to the intakes used in the 2001 ILAW PA (0.084 L, 43.5 L tritium).

Dissolved chemicals are assumed to have air concentrations at 50% of the saturation value given by Henry's Law. The maximum air concentration allowed is the water concentration (in mg/L) times 0.5 L/m^3, the bounding value given in the HSRAM. This approach bypasses the need to classify chemicals as volatiles. In the HSRAM scenarios, the daily air inhalation rates are reduced to 75% of the daily adult rate to represent indoor inhalation rates. The resulting annual air intakes for chemicals are shown in Table A14.

Table A14. Annual Air Intakes by Scenario.

Exposure Scenario	Daily Volume Inhaled (m^3/day)	Exposure Frequency (days/year)	Annual Volume of Air Inhaled (m^3/year)
All Pathways Farmer		***Total***	***8,094***
Ambient	21.88	365	7,986
Shower	0.295	365	108
Native American		***Total***	***11,406***
Ambient	30	365	10,950
Sweat Lodge	1.25	365	456
Columbia River Population		***Total***	***8,094***
Ambient	21.978	365	8,022
Shower	0.197	365	72
HSRAM Industrial		***Total***	***5,049***
Ambient	20	250	5,000
Shower	0.197	250	49
HSRAM Recreational		***Total***	***0.69 / 1.38***
Ambient	0	7	0.00
Shower	0.0985 / 0.197	7	0.69 / 1.38
HSRAM Residential		***Total***	***5,547***
Ambient	15	365	5,475
Shower	0.197	365	72
HSRAM Agricultural		***Total***	***5,547***
Ambient	15	365	5,475
Shower	0.197	365	72

Notes:
- The breathing rates are from Table A11, with the exception of the NASR. The NASR breathing rate for ambient conditions is from the CRCIA.
- In the HSRAM recreational scenario inhalation of volatiles occurs during the shower only. Non-carcinogens are inhaled at the child's rate (0.0985 m^3/d), while carcinogens are inhaled at the adult's rate (0.197 m^3/d).
- The annual volume of air inhaled is calculated as the product of the daily volume inhaled and the exposure frequency.

The air concentration for each chemical is calculated using the unitless Henry's Law Constants from Table A3. Owing to ventilation effects, the actual air concentration will not be at the upper limit given by Henry's law. The average saturation fraction is 50% in analogy with the relative humidity. The formula used for this purpose is shown below. To express the air concentration in terms of the equivalent volume of water per m^3 of air one uses the ratio C_A/C_W. This ratio is not allowed to exceed the HSRAM number (0.5 L/m^3).

$$P_{GAS} = \frac{H'\ R\ T\ C_W}{(1000\ \text{mg/g})\, M_{MOLE}}$$

$$C_A = F_{SAT} \frac{(1000\ \text{L/m}^3)(1000\ \text{mg/g})\, M_{MOLE}}{R\ T} P_{GAS}$$

$$C_A = F_{SAT}(1000\ \text{L/m}^3)H'\, C_W$$

where,

C_A	=	concentration of the chemical in air, in mg/m^3
C_W	=	concentration of the dissolved chemical in water, in mg/L
F_{SAT}	=	fraction of the upper limit concentration given by Henry’s Law that is likely to be present on the average, 50% is assumed
H’	=	unitless Henry’s Law Constant from Table A3
M_{MOLE}	=	molecular weight of the compound, in g/mole
P_{GAS}	=	partial pressure of the chemical in the air, in atm
R	=	ideal gas law constant, 0.082057 L-atm/mole-K
T	=	absolute temperature of the gas, 298.15 K (20 C)
1000 L/m^3	=	volume conversion factor
1000 mg/g	=	mass conversion factor

The airborne chemical concentrations also have a lower bound calculated from the non-tritium annual water inhalation volumes (L/y) shown in Table A13 divided by the annual air inhalation volumes (m^3/y) shown in Table A14. In this way the chemicals with very small Henry’s Law constants are treated as any inert material would be.

A3.3 External Exposure Times

The external dose from radionuclides in soil depends on the radionuclide concentration (in Ci/m^2) and the time of exposure (in hours). The exposure scenarios define what the radionuclide concentration will be. This section discusses the determination of the effective time of exposure for each exposure scenario. The annual exposure times are listed in Table A15.

During the drilling operation, the worker is exposed to varying dose rates. Until the waste is exhumed this dose rate is zero. While the waste comes from the hole, the dose rate is high. Since the volume of waste exhumed is small (less than 1 m^3), the dose rate varies inversely with the square of the worker's distance from the waste. The waste is soon covered with clean soil from deeper in the well, which reduces the dose rate. To represent the potential dose to the worker, the waste is assumed spread near the well to a depth of 5 cm. The volume of soil tailings from a well 8 inches in diameter and 100 m deep is 3.2 m^3. If this volume of soil is spread to an average depth of 5 cm, its area is 86 m^2. The external dose rate factors from an infinite slab that is 5 cm thick are used to estimate the dose from 40 hours of exposure. This approach differs from previous performance assessments, which assume the well tailings are mixed with the soil in an area of 100 m^2 to a depth of 15 cm. The approach used in this report leads to larger external doses for the well driller.

Table A15. Annual External Exposure Times.

Exposure Scenario	Daily (hours/day)	Dose Rate Reduction Factor	Exposure Frequency (days/year)	Annual Exposure Time (hours/year)
Irrigated Land				
Well-Driller	8	1	5	40
Suburban Garden	2	0.5	180	180
Rural Pasture	4	0.5	180	360
Commercial Farm	8	0.5	180	720
All Pathways Farmer	12	0.941	365	4,120
Native American	24	0.8	365	7,008
Columbia River Population	24	0.5	365	4,380
HSRAM Industrial	8	0.8	146	934
HSRAM Recreational	8	0.8	7	45
HSRAM Residential	24	0.8	365	7,008
HSRAM Agricultural	24	0.8	365	7,008
Shoreline Sediments				
All Pathways Farmer	8	0.2	7	11
Native American	12	0.2	270	648
Columbia River Population	5	0.2	5	5
HSRAM Recreational	8	0.2	7	11
HSRAM Residential	8	0.2	7	11
HSRAM Agricultural	8	0.2	7	11
Swimming and Boating				
Native American	2.6	0.5	70	91
HSRAM Recreational	2.6	0.5	7	9.1
HSRAM Residential	2.6	0.5	7	9.1
HSRAM Agricultural	2.6	0.5	7	9.1

Notes:

- The Annual Exposure Time for the Post-Intrusion Resident is reduced because of the small size of the contaminated area. For the All Pathways Farmer it is the total time outdoors plus one-third of the total time indoors. For the Native American it is the same as the HSRAM Residential and HSRAM Agricultural. The Columbia River Population uses a value from prior performance assessments.
- The HSRAM Residential and Agricultural parameters have been assumed to match the parameters for the HSRAM Recreational Scenario.
- The annual external exposure time is calculated as the product of the daily time, the reduction factor, and the exposure frequency.

For the post-intrusion scenarios, the contamination is localized to the area contaminated by the exhumed waste. The external dose rate is greatest in the center of this area. At the edge of the contaminated area the dose rate has dropped to roughly half the value at the center. At a distance of 5 meters from the edge of the contamination the dose rate has dropped by an order of magnitude. Note that the dramatic decrease in dose rate is not the case for the airborne dust concentration. The annual average concentration of suspended dust from the garden decreases by diffusion and turbulent mixing rather slowly with distance, falling to perhaps half the peak value at a distance of 100 m in the downwind direction.

In the post-intrusion scenarios, because the external dose rate decreases rapidly with distance from the contaminated area, the time indoors or asleep (Table A9) will be assigned zero exposure. It will be assumed that the resident spends most of the time outdoors away from the contaminated area. The annual average exposure is half the peak value for an infinite plane because the exposed individual spends time in all parts of the contaminated area. For comparison with the effective annual exposure times shown in Table A15, the 2001 ILAW PA (DOE/ORP-2000-24) used 900 hours, the Grouted Waste PA (WHC-SD-WM-EE-004) used 4,383 hours, and the 200 West Area Burial Ground PA (WHC-EP-0645) used 3,260 hours. In addition, the prior Hanford PA's spread the exposure over the entire year rather than calculating the accumulated dose during the first half of the year.

In the irrigation scenarios most of the area near the person's dwelling is contaminated. The extent of the contaminated areas will affect the calculation of external dose in the two exposure situations. The exposure to soil contamination is divided into two time periods during the year. The first period is the time actually spent standing in the contamination. The second period is the total time near the contamination, or indoors.

In the irrigation scenarios, it is assumed that the entire time outdoors (1800 hours) is spent in exposure conditions similar to the center of an irrigated field. However, the dose rate indoors is reduced by a factor of 3. This factor of 3 is discussed in detail in NUREG/CR-5512, Section 6.7.4. Therefore the effective time of exposure at the unshielded dose rate is 4,120 hours per year, as shown below.

$$(1{,}800 \text{ hr}) + (3{,}102 + 3{,}858 \text{ hr})/3 = 4{,}120 \text{ hours}$$

The dose rate reduction factor shown in Table A15 is calculated from this effective exposure time for completeness. The calculation is shown below.

$$(4{,}120 \text{ h/y}) / (12 \text{ h/d} * 365 \text{ d/y}) = 0.941$$

The 2001 ILAW PA used the same time period for the all pathways farmer, 4,120 h. The Grouted Waste performance assessment used an effective time of 4,383 hours and the 200 West Area Burial Ground performance assessment used an effective time of 3,260 hours.

The Native American exposure scenario also uses 7,008 h/y for the effective external annual exposure time. This is unchanged from the 2001 ILAW PA. However, when the contaminated water is from the Columbia River there is now an additional contribution from shoreline sediments and swimming and boating. These were not included in the 2001 ILAW PA.

The annual exposure time for the Columbia River population is chosen to be 4,380 hours (12 h/d for 365 d). This is the same as used in prior performance assessments.

For the HSRAM scenarios, the external exposure parameters for irrigated land are from the HSRAM. The shoreline, swimming and boating activities for the residential and agricultural scenarios are assumed to match the recreational scenario.

A3.4 Absorption Through the Skin

Each exposure scenario includes dermal contact with the contaminated medium. The driller and post-intrusion resident get the contaminated soil on their skin. The ground water scenarios have contaminated water being used for showers and saunas. This section evaluates the likely intakes due to contaminants being absorbed through the skin into body fluids.

A3.4.1 Dermal Absorption of Radionuclides

The internal dose from radionuclides absorbed through the skin is the product of the amount absorbed each day and an internal dose factor for dermal absorption. Internal dose factors for radionuclides absorbed through the skin can be estimated by dividing the ingestion dose factor by the gut-to-body-fluid transfer fraction (f1). This is somewhat inexact because the material in the gut is wet and contains a variety of chemicals secreted by the body to aid in the absorption of nutrients. In addition, the interior surface area of the small intestine is larger than the skin area of the entire body by two orders of magnitude.

The amount absorbed through the skin depends on the surface concentration of the contaminant, the area contaminated, and how often this happens during the year. The transfer from the skin to the body fluids is assumed proportional to the f1 parameter. The annual intake would then be multiplied by the internal dose factor constructed by dividing the ingestion dose factor by the f1. The f1 transfer fraction thus cancels out of the calculation, and dermal contact can be regarded as another type of ingestion dose.

An exception is for tritium as water vapor. The inhalation dose factor for tritium includes absorption through the skin in addition to the lungs by increasing the value by 50%. The ingestion dose factor is not modified.

<u>Contaminated Soil.</u> Soil adheres to the skin, permitting materials in the soil to be absorbed through the skin into body fluids. The adult body has a median skin area of about 20,000 cm^2, Chapter 6 (EPA/600-P-95/002Fa). The recommended area for contact with soil outdoors is 5,000 cm^2, which is 25% of the total. Typical soil adherence values range from 0.1 mg/cm^2 to 5 mg/cm^2 (EPA/600-P-95/002Fa). Actual soil adherence depends on soil properties such as moisture content and particle size, type of activity, and parts of the body surface exposed. The values selected for the performance assessment exposure scenarios are shown in Table A16. The numbers are at the low end of the range, but are consistent with values selected for the HSRAM and NASR scenarios.

A small fraction of the contamination present on the skin will be absorbed into the body through the skin. This fraction is assumed to be 0.001 times the f1 value based on typical values for the dermal absorption factor for inorganic chemicals (see Table A20). Table A16 summarizes the affected skin areas, soil adherence, and annual contact events for each of the exposure scenarios. The product of these factors gives the equivalent annual soil ingestion due to dermal contact. The values shown are much smaller than the values for direct ingestion of soil presented in Table A8 (less than 3%). Hence the approach taken in DOE/RL-91-45 to neglect dermal absorption of radionuclides will be adopted in this report also.

Table A16. Dermal Absorption of Radionuclides in Soil.

Scenario	Soil Adherence (mg/cm^2)	Exposure Frequency (days/year)	Equivalent Ingestion (g/year)	Fraction of Inadvertent Soil Ingested
Well-Driller	0.25	5	0.0063	1.3%
Post-Intrusion Scenarios	0.25	180	0.23	1.3%
All Pathways Farmer	0.25	365	0.46	1.3%
Native American	1.0	365	1.8	2.5%
Columbia River Population	0.2	365	0.37	1.0%

Notes:

- The recommended adult surface area involved in outdoor soil contact is 5,000 cm^2 from the Exposure Factors Handbook, Chapter 6 (EPA/600-P-95/002Fa).
- The "Equivalent Ingestion" is the product of the adult surface area for outdoor contact, the soil adherence, the exposure frequency, and the assumed dermal absorption factor, 0.001.
- The fractions shown in the last column are the annual dermal intake divided by the annual inadvertent soil ingestion shown in Table A7.

Contaminated Irrigation Water. Waterborne contaminants in contact with the skin may potentially be absorbed through the skin into the body fluids. The leading dermal contact events are showers and the sauna or sweat lodge. Since these expose the entire skin surface, the potential for significant absorption exists. However, contact time is limited to 10 or 15 minutes for showers and 1 hour for the sauna or sweat lodge. The recommended adult total surface area is 20,000 cm^2 from the Exposure Factors Handbook, Chapter 6 (EPA/600-P-95/002Fa). Based on this area and typical values for the dermal absorption (permeability) constant (0.01 cm/h from Table A20), the dermal absorption intakes shown in Table A17 may be calculated. The last column in Table A17 shows the ratio of the annual dermal intake to the annual average ingestion intake of water (545 L from Table A4). The dermal absorption adds less than 1 percent to the total. Therefore, the dermal absorption of radionuclides in water will not be explicitly included in the calculations in this report.

Table A17. Dermal Absorption of Radionuclides in Water.

Scenario	Daily Contact Time (hours/day)	Exposure Frequency (days/year)	Equivalent Ingestion (L/year)	Fraction of Total Water Ingested
All Pathways Farmer	0.25	365	1.8	0.3%
Native American Sweat Lodge	1	365	7.3	0.7%
Columbia River Population	0.167	365	1.2	0.2%

Notes:

- The daily contact times are the sweat lodge duration for the Native American, and the shower duration for the others.
- The "Equivalent Ingestion" is the product of the adult surface area (20,000 cm^2), the daily contact time, the exposure frequency, and the assumed permeability coefficient, 0.01 cm/h.
- The fractions shown in the last column are the equivalent ingestion per year divided by the annual water ingestion from Table A4.

A3.4.2 Dermal Absorption of Chemicals

The dermal absorption of chemicals occurs as a result of contact with contaminated soil or water. Annual dermal exposure factors are shown in Table A18 for soil and A19 for water. The exposure factors need to be multiplied by the chemical-specific dermal absorption factor (soil contact) or the permeability coefficient (water contact). Because reference doses and slope factors for dermal exposure have not been developed, a form of route-to-route extrapolation is used. The dermal exposures are treated as a form of ingestion, and the ingestion reference dose and slope factor are used. The only modification factor is the gut-to-body fluid transfer factor (f1). The exposures are adjusted to an effective amount ingested (i.e., outside the body) by dividing by the gut-to-body fluid transfer fraction.

Table A18. Dermal Absorption of Chemicals in Soil.

Scenario	Skin Contact Area (cm^2)	Soil Adherence (mg/cm^2)	Exposure Frequency (days/year)	Annual Dermal Exposure (g/year)
Irrigated Land				
All Pathways Farmer	5,000	0.25	365	456
Native American	5,000	1.0	365	1,825
Columbia River Population	5,000	0.2	180	365
HSRAM Industrial	5,000	0.2	146	146
Recreational -- Child/Adult	2500 / 5000	0.2	7	3.5 / 7
Residential -- Child/Adult	2500 / 5000	0.2	180	90 / 180
Agricultural -- Child/Adult	2500 / 5000	0.2	180	90 / 180
Shoreline Sediment				
All Pathways Farmer	5,000	0.25	7	8.8
Native American	5,000	1.0	270	1,350
Columbia River Population	5,000	0.2	5	5.0
Recreational -- Child/Adult	2500 / 5000	0.2	7	3.5 / 7
Residential -- Child/Adult	2500 / 5000	0.2	7	3.5 / 7
Agricultural -- Child/Adult	2500 / 5000	0.2	7	3.5 / 7

Notes:
- The recommended adult surface area involved in outdoor soil contact is 5,000 cm^2 from the Exposure Factors Handbook, Chapter 6 (EPA/600-P-95/002Fa). The child's surface area for contact with soil outdoors is half the adult value. For the last three HSRAM scenarios, the first 6 years are at the child's rate while the next 24 years are at the adult rate.
- Soil adherence and exposure frequency numbers for the All Pathways and Columbia River scenarios are assumed. Values for the HSRAM scenarios are from the HSRAM. Values for the NASR are from the CRCIA.
- The "Annual Dermal Exposure" is the product of the skin contact area, the soil adherence, and the exposure frequency.
- In the absence of reference doses and slope factors for dermal absorptions, the dermal route is treated as a form of ingestion. The effective amount ingested is the product of the annual dermal exposure and dermal absorption factor (Table A20) divided by the GI absorption factor (Table A20).

The dermal absorption factors for contact with contaminated soil shown in Table A20 are from EPA guidance listed below. Note that values for carbon disulfide and PCBs are given in the second and third reference.

(1) United States Environmental Protection Agency. 1995. Supplemental Guidance to RAGS: Region 4 Bulletins, Human Health Risk Assessment (Interim Guidance). Waste Management Division, Office of Health Assessment. In general, the dermal absorption factor is 1% for organics and 0.1% for inorganics.
(2) United States Environmental Protection Agency. 1992. Dermal Exposure Assessment: Principles and Application. Interim Report. EPA/600/8-91/011B. Office of Research and Development, Washington, D.C. Section 6.3 recommends the use of 6% for PCBs.
(3) ATSDR (Agency for Toxic Substances and Disease Registry). 1992. Toxicological Profile for Carbon Disulfide. ATSDR/U.S. Public Health Service.

Table A19. Dermal Absorption of Chemicals in Water.

Scenario	Daily Dermal Contact Time (hours/day)	Exposure Frequency (days/year)	Annual Dermal Exposure (L/year per cm/h)
All Pathways Farmer Shower	0.25	365	1,825
Native American Sweat Lodge	1	365	7,300
Native American Swimming	2.6	70	3,640
Columbia River Population Shower	0.167	365	1,217
HSRAM Industrial Shower	0.167	250	833
Recreational Shower	0.167	7	23
Surface Water Swimming	2.6	7	364
Residential Shower	0.167	365	1,217
Agricultural Shower	0.167	365	1,217

Notes:
- The "Surface Water Swimming" is not used in the All Pathways Farmer or HSRAM Industrial scenarios. All others use this contact time in addition to contact during bathing.
- The "Annual Dermal Exposure" is the product of the adult surface area (20,000 cm^2), the daily contact time, and the exposure frequency.
- In the absence of reference doses and slope factors for dermal absorptions, the dermal route is treated as a form of ingestion. The effective amount ingested is the product of the annual dermal exposure of water and the permeability coefficient (Table A20) divided by the GI absorption factor (Table A20).

The permeability constants for contact with contaminated water shown in Table A20 are calculated from the formula below from *Dermal Exposure Assessment: Principles and Application. Interim Report* (EPA/600/8-91/011B). Values for the logarithm of the octanol-water constant (Log K_{OW}) and molecular weights (MW) for each chemical are listed in Table A3. The formula below was used even for inorganic compounds, provided there was a value for Log K_{OW}. For the few chemicals with no value for Log K_{OW}, the default value of 0.001 cm/h was used.

$$\text{Log } U_D = 0.71(\text{Log } K_{OW}) - 0.0061{*}MW - 2.72$$

The gastro-intestinal absorption factors shown in Table A20 are from the RAIS database. Values in the database are from a large list of technical publications. The internet address for these references is http://risk.lsd.ornl.gov/tox/giabsref.shtml. The GI absorption factors and references may also be accessed by chemical using http://risk.lsd.ornl.gov/cgi-bin/tox/TOX_select?select=nrad.

Table A20. Dermal Absorption Parameters for Chemicals.

CASRN	Chemical Name	Dermal Absorption Factor	Permeability Constant (cm/h)	GI Absorption Factor (f1)
50-32-8	Benzo[a]pyrene	0.01	1.24E+00	0.31
53-70-3	Dibenz[a,h]anthracene	0.01	2.37E+00	0.31
56-23-5	Carbon tetrachloride	0.01	2.24E-02	0.65
57-12-5	Cyanide, free	0.01	8.66E-04	0.17
57-14-7	1,1-Dimethylhydrazine	0.01	1.17E-04	0.5
57-55-6	Propylene glycol (1,2-Propanediol)	0.01	1.45E-04	0.5
58-89-9	gamma-Benzene hexachloride (gamma-Lindane)	0.01	1.40E-02	0.97
60-34-4	Methylhydrazine	0.01	1.79E-04	0.5
60-57-1	Dieldrin	0.01	6.17E-02	0.5
62-75-9	N-Nitrosodimethylamine	0.01	2.65E-04	0.5
64-18-6	Formic acid	0.01	4.13E-04	0.5
67-56-1	Methanol (Methyl alcohol)	0.01	3.45E-04	0.8
67-64-1	Acetone (2-Propanone)	0.01	5.69E-04	0.83
67-66-3	Chloroform	0.01	8.92E-03	0.2
71-36-3	n-Butyl alcohol (n-Butanol)	0.01	2.84E-03	0.5
71-43-2	Benzene	0.01	2.07E-02	0.97
71-55-6	1,1,1-Trichloroethane (Methyl chloroform)	0.01	1.71E-02	0.9
72-20-8	Endrin	0.01	4.45E-02	0.02
74-83-9	Bromomethane	0.01	3.51E-03	0.8
74-87-3	Methyl chloride (Chloromethane)	0.01	4.15E-03	0.8
75-00-3	Ethyl Chloride	0.01	7.97E-03	0.8
75-01-4	Vinyl chloride (Chloroethene)	0.01	1.12E-02	1
75-05-8	Acetonitrile	0.01	6.14E-04	0.8
75-07-0	Acetaldehyde	0.01	5.89E-04	0.8
75-09-2	Dichloromethane (Methylene chloride)	0.01	4.46E-03	0.95
75-15-0	Carbon disulfide	0.25	1.56E-02	0.63
75-21-8	Ethylene Oxide (Oxirane)	0.01	6.28E-04	0.8
75-34-3	1,1-Dichloroethane (Ethylidene chloride)	0.01	8.86E-03	1
75-35-4	1,1-Dichloroethylene	0.01	1.59E-02	1
75-45-6	Chlorodifluoromethane	0.01	3.31E-03	0.8
75-68-3	Chloro-1,1-difluoroethane, 1-	0.01	1.33E-02	0.8
75-69-4	Trichlorofluoromethane	0.01	1.73E-02	0.23
75-71-8	Dichlorodifluoromethane	0.01	1.19E-02	0.23
76-13-1	1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113)	0.01	2.40E-02	0.8
76-44-8	Heptachlor	0.01	2.16E-01	0.72
78-87-5	1,2-Dichloropropane	0.01	9.92E-03	0.74
78-93-3	Methyl ethyl ketone (2-Butanone)	0.01	1.11E-03	0.8
79-00-5	1,1,2-Trichloroethane	0.01	6.43E-03	0.81
79-01-6	Trichloroethylene	0.01	1.57E-02	0.15
79-10-7	2-Propenoic acid (Acrylic acid)	0.01	1.23E-03	0.5
79-34-5	1,1,2,2-Tetrachloroethane (Acetylene tetrachloride)	0.01	8.97E-03	0.7
82-68-8	Pentachloronitrobenzene (PCNB)	0.01	5.93E-02	0.8
83-32-9	Acenaphthene	0.01	1.33E-01	0.31
84-66-2	Diethyl phthalate	0.01	4.39E-03	0.9
84-74-2	Dibutyl phthalate	0.01	5.99E-02	1

Table A20. Dermal Absorption Parameters for Chemicals.

CASRN	Chemical Name	Dermal Absorption Factor	Permeability Constant (cm/h)	GI Absorption Factor (f1)
85-68-7	Butyl benzyl phthalate	0.01	5.41E-02	0.61
87-68-3	Hexachlorobutadiene	0.01	1.21E-01	0.5
87-86-5	Pentachlorophenol	0.01	1.95E-01	1
88-06-2	2,4,6-Trichlorophenol	0.01	4.96E-02	0.5
88-85-7	2-sec-Butyl-4,6-dinitrophenol (Dinoseb)	0.01	2.20E-02	0.5
91-20-3	Naphthalene	0.01	6.94E-02	0.8
92-52-4	1,1'-Biphenyl	0.01	1.46E-01	0.5
95-50-1	1,2-Dichlorobenzene (ortho-)	0.01	6.59E-02	0.8
95-63-6	1,2,4-Trimethylbenzene	0.01	1.33E-01	0.8
98-86-2	Acetophenone	0.01	4.67E-03	0.8
98-95-3	Nitrobenzene	0.01	6.96E-03	0.97
100-25-4	1,4-Dinitrobenzene (para-)	0.01	1.95E-03	0.5
100-41-4	Ethyl benzene	0.01	7.39E-02	0.97
100-42-5	Styrene	0.01	5.49E-02	0.8
100-51-6	Benzyl alchohol	0.01	2.52E-03	0.66
106-46-7	1,4-Dichlorobenzene (para-)	0.01	6.69E-02	0.9
106-93-4	1,2-Dibromoethane (Ethylene dibromide)	0.01	3.35E-03	0.8
106-99-0	1,3-Butadiene	0.01	2.31E-02	0.8
107-02-8	Acrolein	0.01	8.53E-04	0.8
107-05-1	3-Chloropropene (Allyl chloride)	0.01	1.53E-02	0.8
107-06-2	1,2-Dichloroethane (Ethylene chloride)	0.01	5.34E-03	1
107-13-1	Acrylonitrile	0.01	1.36E-03	0.8
108-10-1	Methyl isobutyl ketone (4-Methyl-2-pentanone)	0.01	3.97E-03	0.8
108-67-8	1,3,5-Trimethylbenzene	0.01	9.44E-02	0.8
108-87-2	Methyl cyclohexane	0.01	1.75E-01	0.8
108-88-3	Toluene (Methyl benzene)	0.01	4.53E-02	0.8
108-90-7	Chlorobenzene	0.01	4.07E-02	0.31
108-94-1	Cyclohexanone	0.01	1.80E-03	0.8
108-95-2	Phenol (Carbolic acid)	0.01	5.53E-03	0.9
110-00-9	Furan (Oxacyclopentadiene)	0.01	6.55E-03	0.8
110-54-3	n-Hexane	0.01	3.34E-01	0.8
110-86-1	Pyridine	0.01	1.82E-03	0.5
111-76-2	2-Butoxyethanol (Ethylene Glycol Monobutyl Ether)	0.01	1.41E-03	0.5
111-90-0	2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether)	0.01	1.20E-04	0.5
117-81-7	Di (2-ethylhexyl) phthalate (DEHP)	0.01	1.97E+00	0.19
117-84-0	Di-n-octylphthalate	0.01	4.45E+00	0.9
118-74-1	Hexachlorobenzene	0.01	4.08E-01	0.5
120-82-1	1,2,4-Trichlorobenzene	0.01	1.07E-01	0.97
121-44-8	Triethylamine	0.01	4.92E-03	0.8
122-39-4	Diphenylamine	0.01	5.40E-02	0.5
123-91-1	1,4-Dioxane (Diethylene oxide)	0.01	3.55E-04	0.8
126-73-8	Tributyl Phosphate	0.01	3.13E-02	0.5
126-98-7	2-Methyl-2-propenenitrile (Methacrylonitrile)	0.01	2.26E-03	0.8
127-18-4	1,1,2,2-Tetrachloroethylene	0.01	4.81E-02	1

Table A20. Dermal Absorption Parameters for Chemicals.

CASRN	Chemical Name	Dermal Absorption Factor	Permeability Constant (cm/h)	GI Absorption Factor (f1)
141-78-6	Ethyl acetate (Acetic acid, ethyl ester)	0.01	1.82E-03	0.8
156-59-2	cis-1,2-Dichloroethylene	0.01	1.02E-02	1
206-44-0	Fluoranthene (1,2-Benzacenaphthene)	0.01	5.13E-01	0.31
309-00-2	Aldrin	0.01	4.67E-01	0.5
319-84-6	alpha-Benzene hexachloride (alpha-Lindane)	0.01	1.60E-02	0.97
319-85-7	beta-Benzene hexachloride (beta-Lindane)	0.01	1.55E-02	0.91
621-64-7	N-Nitrosodi-N-propylamine	0.01	2.83E-03	0.25
1314-62-1	Vanadium pentoxide	0.001	1.90E-02	0.2
1330-20-7	Xylenes (mixtures)	0.01	7.04E-02	0.92
1336-36-3	Polychlorinated Biphenyls (high risk)	0.06	9.22E-01	0.9
1336-36-3	Polychlorinated Biphenyls (low risk)	0.06	9.22E-01	0.9
1336-36-3	Polychlorinated Biphenyls (lowest risk)	0.06	9.22E-01	0.9
6533-73-9	Thallium carbonate	0.01	6.45E-07	0.5
7429-90-5	Aluminum	0.001	2.14E-03	0.1
7439-96-5	Manganese	0.001	1.28E-03	0.04
7439-98-7	Molybdenum	0.001	7.21E-04	0.38
7440-02-0	Nickel (soluble salts)	0.001	3.29E-04	0.27
7440-22-4	Silver	0.001	6.10E-04	0.18
7440-24-6	Strontium, Stable	0.001	8.11E-04	0.2
7440-31-5	Tin	0.001	2.88E-03	0.1
7440-36-0	Antimony	0.001	1.09E-03	0.02
7440-38-2	Arsenic (inorganic)	0.001	1.94E-03	0.41
7440-39-3	Barium	0.001	4.03E-04	0.07
7440-41-7	Beryllium and compounds	0.001	6.61E-04	0.01
7440-42-8	Boron and borates only	0.001	2.28E-03	0.9
7440-43-9	Cadmium	0.01	3.50E-04	0.01
7440-48-4	Cobalt	0.001	1.21E-03	0.8
7440-66-6	Zinc and compounds	0.001	3.43E-04	0.2
7487-94-7	Mercuric chloride	0.001	2.94E-05	0.07
7664-41-7	Ammonia	0.001	1.57E-04	0.2
7723-14-0	Phosphorus, white	0.001	7.60E-04	0.2
7782-41-4	Fluorine (soluble fluoride)	0.001	1.60E-03	0.97
7782-49-2	Selenium and compounds	0.001	9.05E-04	0.44
8001-35-2	Toxaphene	0.01	7.24E-02	0.5
14797-55-8	Nitrate	0.001	1.12E-03	0.5
14797-65-0	Nitrite	0.001	1.09E-03	0.5
16065-83-1	Chromium (III) (insoluble salts)	0.001	1.00E-03	0.005
18540-29-9	Chromium (VI) (soluble salts)	0.001	1.00E-03	0.02
none	Uranium (soluble salts)	0.001	1.00E-03	0.85

Notes:

- Dermal Absorption Factors and GI Absorption Factors are from the EPA references listed in the text. The listing in this table is from the Risk Assessment Information System (RAIS) as of June, 2003.
- The Permeability Constants are calculated from the molecular weight and octanol-water constants or the default value of 0.001 cm/h as described in the text.

A3.5 Internal Dose Factors for Radionuclides

Internal dose factors specify the effective dose equivalent (EDE) from a unit intake (ingested or inhaled) of a radionuclide. The dose is accumulated over a period of 50 years, known as the dose commitment period. This dose commitment period was set by the ICRP in Publication 26 (1977) when determining internal dose and relating it to an equivalent whole body exposure.

If a nuclide has radioactive progeny with short half-lives (i.e. nuclides with a "+D" at the end of the name), then the internal dose factors for these progeny are included with the parent isotope. It is assumed that the progeny are in secular equilibrium with the parent nuclide. The internal dose factors for the progeny are multiplied by the branching ratio (see Table A1) and added to the parent dose factor.

Four internal dose factor collections will be considered. The first was widely used in performance assessments for the United States Department of Energy (DOE/EH-0071). The second was prepared under the sponsorship of the United States Environmental Protection Agency (EPA-520/1-88-020). This set is now recommended for use in performance assessments at DOE sites (DOE/LLW-93 and DOE M 435.1-1 Implementation Guide Chapter IV). The third was computed for the GENII software (PNNL-6584), which is often used at the Hanford Site. The GENII internal dose factors are based on the 1993 revision (WHC-SD-WM-TI-596). The fourth set of internal dose factors uses improved anatomical models and revised metabolic data adopted by the International Commission on Radiological Protection beginning in 1990. The summary compilation of internal dose factors for various age groups was released in ICRP Publication 72.

The internal dose factors from the first three collections (GENII, EPA, and DOE) are listed in Tables A21 (ingestion) and A22 (inhalation). The ICRP 72 internal dose factors for the average adult are shown in Table A23. The internal dose factors have been converted to the common units of mrem per pCi intake. For the ingestion dose factors, the assumed values for f1, which is the fraction of the activity ingested that enters body fluids is shown. For the inhalation dose factors, the assumed activity median aerodynamic diameter of the particles is 1 µm.. The lung model category is shown in the tables. The "Water" for tritium stands for tritiated water vapor (HTO), and includes a 50 percent increase due to absorption through the skin. The "Organic" for C-14 means that the carbon is assumed to have an organic chemical form rather than gaseous. The "D", "W", and "Y" mean the material clears the lungs in a matter of days, weeks, or years, respectively. The improved lung model uses the designations "F", "M", and "S" which stand for fast, moderate, and slow. The chemical forms originally classified as "D", "W", or "Y" should be now be regarded as "F", "M", or "S", respectively.

The assumed lung clearance rate for many of the radionuclides was changed to incorporate the recommendations of the ICRP in Report Number 71 (ICRP 1996). Based on a literature review, the ICRP recommended certain default types for particulate aerosol when no specific information is available. No recommendations were given for beryllium, silicon, titanium, vanadium, cadmium, indium, tin, promethium, gadolinium, rhenium, bismuth, actinium, or protactinium. For these elements, the solubility class with the largest inhalation dose factor was selected. An exception to this approach was made for titanium. The largest inhalation dose factors are for class Y material, but the slow lung clearance was only observed for one compound, $SrTiO_3$. Because this compound is unlikely to be found in Hanford tank waste, the titanium compounds were assumed to be class D.

Comparison ratios of the GENII and DOE dose factors divided by the EPA dose factors are shown in Tables A21 and A22. Dose factors that differ less than 5% from the EPA numbers are not shown in the ratio columns. The only nuclides with differences greater than 25 percent are Co-60, Nb-94, Tc-99, Ru-106, Ag-108m, In-115, Sn-126, Re-187, Bi-207, Ra-226, Ra-228, Th-228, Np-237, Pu-241, and Bk-247.

The dose factor collection from the EPA (EPA-520/1-88-020) will be used in the tank waste PA. These are the only internal dose factors currently approved by the DOE for use in performance assessments (DOE M 435.1-1). The difference between the GENII, EPA, and DOE internal dose factors is minor because they are all based on the methods given in ICRP 30. However, the difference between the EPA and the ICRP 72 internal dose factors is appreciable in some cases. The ratios between the EPA and ICRP 72 internal dose factors are shown in Table A23.

The internal dose factors for Nb-91 are not listed in any dose factor collection and were assumed bounded by the values for Nb-93m. Both nuclides emit low energy electrons and photons, as shown on the nuclear decay data summary of Table A24. For Nb-91, there is a continuous spectrum of low energy photons associated with the electron capture and positron decay. However, this continuous spectrum is a minor addition to the photon spectrum. The total electron plus photon energy for Nb-91 (15 keV) is less than that for Nb-93m (26 keV). Therefore, the internal dose factor for Nb-91 should be less than that for Nb-93m.

An additional consideration is the half-life of the two isotopes compared with expected residence times in the body. Inhalation class Y niobium is retained in the lungs for a considerable length of time. Most is removed during the first several years, but some is retained indefinitely. The organ with the largest dose for class Y Nb-93m is the lung. Most (87%) of the dose from Nb-93m accrues during the first 10 years after inhalation. Thus, the effect of Nb-93m's shorter half-life is small. It will be assumed that the internal dose factors for Nb-91 are bounded by those for Nb-93m.

In addition to Nb-91, the internal dose factors for Po-209 are not listed in any dose factor collection and were computed by comparison with Po-210. Corrections were made for the energy of the alpha particles emitted, and the decay half-life using the equation shown below.

$$\text{Dose Factor} \propto \frac{E_\alpha}{\lambda_{eff}}\left[1 - \mathrm{Exp}\left(-\lambda_{eff} T_d\right)\right]$$

where

E_α = total alpha energy per decay. For Po-209 this is 4.866 Mev per decay, while for Po-210 this is 5.304 Mev per decay.

λ_{eff} = effective removal constant, which combines both the biological elimination and the radioactive decay of the nuclide, i.e., $\lambda_{eff} = \lambda_{bio} + \lambda_{rad}$.

T_d = dose commitment period used in the dose factor collections shown in Tables A21 and A22, namely, 50 years.

From ICRP 30, the biological removal half time for polonium is 50 days (λ_{bio}=Ln(2)/50d =0.01386 per day). The decay half-life of Po-209 is 102 year (λ_{rad}=Ln(2)/102y/365.25=0.00002 per day), thus its λ_{eff} is 0.01388 per day. The decay half-life of Po-210 is 138.38 days (λ_{rad}=Ln(2)/138.38d=0.00501 per day), thus its λ_{eff} is 0.01887 per day. Thus, the dose integration term in brackets is nearly equal to 1 after 50 years. The ratio of Po-209 to Po-210 internal dose factors is shown below. This ratio was applied to the Po-210 inhalation and ingestion dose factors to arrive at the Po-209 internal dose factors.

$$\frac{\text{Po - 209 Dose Factor}}{\text{Po - 210 Dose Factor}} = \frac{(4.866\ \text{MeV})(0.01887\ \text{per day})}{(5.304\ \text{MeV})(0.01388\ \text{per day})} = 1.247$$

Special groups of people such as children and diabetics, will have different internal dose factors due to differences in organ mass and retention times in the various tissues of the body. Internal dose factors for different age groups have been computed by the ICRP in Publication 72 (1996). Unit dose factors for individuals whose metabolic characteristics differ considerably from those of the reference individual will also differ from those presented in Tables A21 and A22. As explained in DOE M 435.1-1 Chapter IV, the use of dose factors for representative members of the public is desirable to avoid overly conservative results. A bounding case exposure scenario evaluates possible upper limits.

Absorption through the skin, and injection from an injury are not considered since they are not likely to add significantly to the doses computed in the intruder and irrigation scenarios. These may be computed using an internal dosimetry program such as CINDY (PNNL-7493). Values have been published (PNNL-10190) and are basically the ingestion dose factor divided by the internal transfer factor (f1).

Any special exposure pathways associated with extended dermal contact with contaminated soil or vegetation will require appropriate dermal absorption dose factors. Dermal absorption methods for radionuclides have been included in the MEPAS[1] program (PNNL-10523).

Table A21. Ingestion Dose Factors, mrem/pCi Ingested.

Nuclide	f1	GENII	EPA	DOE	GENII / EPA	DOE / EPA
H-3	1	6.12E-08	6.40E-08	6.30E-08		
Be-10	0.005	4.70E-06	4.66E-06	4.20E-06		0.90
C-14	1	2.06E-06	2.09E-06	2.10E-06		
Na-22	1	1.06E-05	1.15E-05	1.20E-05	0.92	
Al-26	0.01	1.42E-05	1.46E-05	1.30E-05		0.89
Si-32+D	0.01	1.11E-05	1.10E-05	9.40E-06		0.86
Cl-36	1	2.95E-06	3.03E-06	3.00E-06		
K-40	1	1.79E-05	1.86E-05	1.90E-05		
Ca-41	0.3	1.20E-06	1.27E-06	1.20E-06		
Ti-44+D	0.01	2.35E-05	2.46E-05	2.04E-05		0.83

[1]MEPAS is a registered trademark of Battelle Memorial Institute.

Table A21. Ingestion Dose Factors, mrem/pCi Ingested.

Nuclide	f1	GENII	EPA	DOE	GENII / EPA	DOE / EPA
V-49	0.01	6.04E-08	6.14E-08	5.40E-08		0.88
Mn-54	0.1	2.76E-06	2.77E-06	2.70E-06		
Fe-55	0.1	6.15E-07	6.07E-07	5.80E-07		
Fe-60+D	0.1	na	1.52E-04	1.50E-04		
Co-60	0.3	2.65E-05	2.69E-05	2.60E-05		
Ni-59	0.05	2.05E-07	2.10E-07	2.00E-07		
Ni-63	0.05	5.72E-07	5.77E-07	5.40E-07		0.94
Se-79	0.8	8.33E-06	8.70E-06	8.30E-06		
Rb-87	1	4.73E-06	4.92E-06	4.80E-06		
Sr-90+D	0.3	1.31E-04	1.53E-04	1.40E-04	0.85	0.91
Zr-93	0.002	1.64E-06	1.66E-06	1.60E-06		
Nb-91	0.01	5.05E-07	5.22E-07	5.30E-07		
Nb-93m	0.01	5.05E-07	5.22E-07	5.30E-07		
Nb-94	0.01	7.25E-06	7.14E-06	5.10E-06		0.71
Mo-93	0.8	1.21E-06	1.35E-06	1.30E-06	0.90	
Tc-99	0.8	2.23E-06	1.46E-06	1.30E-06	1.53	0.89
Ru-106+D	0.05	2.73E-05	2.74E-05	2.10E-05		0.77
Pd-107	0.005	1.50E-07	1.49E-07	1.40E-07		0.94
Ag-108m+D	0.05	7.58E-06	7.62E-06	7.50E-06		
Cd-109	0.05	1.32E-05	1.31E-05	1.20E-05		0.91
Cd-113m	0.05	1.62E-04	1.61E-04	1.50E-04		0.93
In-115	0.02	8.68E-05	1.58E-04	1.40E-04	0.55	0.89
Sn-121m+D	0.02	2.24E-06	2.25E-06	1.99E-06		0.88
Sn-126+D	0.02	2.08E-05	2.10E-05	1.83E-05		0.87
Sb-125	0.1	2.83E-06	2.81E-06	2.40E-06		0.85
Te-125m	0.2	3.72E-06	3.67E-06	3.40E-06		0.93
I-129	1	2.49E-04	2.76E-04	2.80E-04	0.90	
Cs-134	1	6.82E-05	7.33E-05	7.40E-05	0.93	
Cs-135	1	6.86E-06	7.07E-06	7.10E-06		
Cs-137+D	1	4.74E-05	5.00E-05	5.00E-05	0.95	
Ba-133	0.1	3.05E-06	3.40E-06	3.20E-06	0.90	0.94
Pm-147	0.0003	1.06E-06	1.05E-06	9.50E-07		0.91
Sm-147	0.0003	1.86E-04	1.85E-04	1.80E-04		
Sm-151	0.0003	3.87E-07	3.89E-07	3.40E-07		0.88
Eu-150	0.001	6.34E-06	6.36E-06	6.20E-06		
Eu-152	0.001	6.48E-06	6.48E-06	6.00E-06		0.93
Eu-154	0.001	9.61E-06	9.55E-06	9.10E-06		
Eu-155	0.001	1.53E-06	1.53E-06	1.30E-06		0.85
Gd-152	0.0003	1.61E-04	1.61E-04	1.50E-04		0.93
Ho-166m	0.0003	8.13E-06	8.07E-06	7.80E-06		
Re-187	0.8	1.45E-08	9.51E-09	8.30E-09	1.52	0.87
Tl-204	1	3.46E-06	3.36E-06	3.20E-06		

Table A21. Ingestion Dose Factors, mrem/pCi Ingested.

Nuclide	f1	GENII	EPA	DOE	GENII / EPA	DOE / EPA
Pb-205	0.2	1.64E-06	1.63E-06	1.50E-06		0.92
Pb-210+D	0.2	5.40E-03	5.37E-03	5.11E-03		
Bi-207	0.05	5.49E-06	5.48E-06	4.90E-06		0.89
Po-209	0.1	2.39E-03	2.37E-03	2.00E-03		0.84
Po-210	0.1	1.90E-03	1.90E-03	1.60E-03		0.84
Ra-226+D	0.2	9.51E-04	1.33E-03	1.10E-03	0.72	0.83
Ra-228+D	0.2	8.44E-04	1.44E-03	1.20E-03	0.59	0.84
Ac-227+D	0.001	1.44E-02	1.48E-02	1.46E-02		
Th-228+D	0.0002	5.79E-04	8.11E-04	7.54E-04	0.71	0.93
Th-229+D	0.0002	3.87E-03	4.03E-03	3.91E-03		
Th-230	0.0002	5.48E-04	5.48E-04	5.30E-04		
Th-232	0.0002	2.73E-03	2.73E-03	2.80E-03		
Pa-231	0.001	1.06E-02	1.06E-02	1.10E-02		
U-232	0.05	1.31E-03	1.31E-03	1.30E-03		
U-233	0.05	2.90E-04	2.89E-04	2.70E-04		0.93
U-234	0.05	2.84E-04	2.83E-04	2.60E-04		0.92
U-235+D	0.05	2.67E-04	2.67E-04	2.51E-04		0.94
U-236	0.05	2.69E-04	2.69E-04	2.50E-04		0.93
U-238+D	0.05	2.70E-04	2.68E-04	2.43E-04		0.91
Np-237+D	0.001	5.22E-03	4.44E-03	3.90E-03	1.17	0.88
Pu-236	0.001	1.16E-03	1.17E-03	1.30E-03		1.12
Pu-238	0.001	3.19E-03	3.20E-03	3.80E-03		1.19
Pu-239	0.001	3.53E-03	3.54E-03	4.30E-03		1.22
Pu-240	0.001	3.53E-03	3.54E-03	4.30E-03		1.22
Pu-241+D	0.001	6.79E-05	6.85E-05	8.60E-05		1.26
Pu-242	0.001	3.35E-03	3.36E-03	4.10E-03		1.22
Pu-244+D	0.001	3.32E-03	3.32E-03	4.00E-03		1.20
Am-241	0.001	3.62E-03	3.64E-03	4.50E-03		1.24
Am-242m+D	0.001	3.50E-03	3.52E-03	4.20E-03		1.19
Am-243+D	0.001	3.62E-03	3.63E-03	4.50E-03		1.24
Cm-242	0.001	1.15E-04	1.15E-04	1.10E-04		
Cm-243	0.001	2.50E-03	2.51E-03	2.90E-03		1.15
Cm-244	0.001	2.01E-03	2.02E-03	2.30E-03		1.14
Cm-245	0.001	3.73E-03	3.74E-03	4.50E-03		1.20
Cm-246	0.001	3.70E-03	3.70E-03	4.50E-03		1.22
Cm-247+D	0.001	3.40E-03	3.42E-03	4.10E-03		1.20
Cm-248	0.001	1.36E-02	1.36E-02	1.60E-02		1.18
Cm-250+D	0.001	7.76E-02	7.77E-02	7.77E-02		
Bk-247	0.001	3.81E-03	4.70E-03	2.30E-03	0.81	0.49
Cf-248	0.001	3.39E-04	3.34E-04	2.80E-04		0.84
Cf-249	0.001	4.75E-03	4.74E-03	4.60E-03		
Cf-250	0.001	2.13E-03	2.13E-03	1.90E-03		0.89

Table A21. Ingestion Dose Factors, mrem/pCi Ingested.

Nuclide	f1	GENII	EPA	DOE	GENII / EPA	DOE / EPA
Cf-251	0.001	4.82E-03	4.85E-03	4.60E-03		0.95
Cf-252	0.001	1.09E-03	1.08E-03	9.40E-04		0.87

Notes:

- GENII ingestion dose factors are based on the 1993 revision (WHC-SD-WM-TI-596). EPA ingestion dose factors from Federal Guidance Report Number 11, EPA-520/1-88-020, Sept 1988. DOE ingestion dose factors from DOE/EH-0071, (DE88-014297), July 1988. All are 50 year committed EDE.
- "f1" is the fraction of the ingested activity reaching body fluids.
- The short-lived radioactive progeny shown on Table A1 are assumed to be in secular equilibrium with their parent nuclide. The dose factors for implicit daughters have been multiplied by the branching ratios in Table A1 and added to the parent dose factor to give the values shown.
- The last two columns show ratios of GENII and DOE ingestion dose factors to the EPA dose factors. Ratios of dose factors within 5% of the EPA value are not shown.

Table A22. Inhalation Dose Factors, mrem/pCi Inhaled.

Nuclide	Lung Model	GENII	EPA	DOE	GENII / EPA	DOE / EPA
H-3	Water	9.02E-08	9.60E-08	9.45E-08	0.94	
Be-10	Y	3.54E-04	3.54E-04	3.50E-04		
C-14	Organic	2.06E-06	2.09E-06	2.10E-06		
Na-22	D	7.11E-06	7.66E-06	8.00E-06	0.93	
Al-26	W	6.95E-05	7.22E-05	5.90E-05		0.82
Si-32+D	Y	1.02E-03	1.03E-03	1.01E-03		
Cl-36	W	2.21E-05	2.19E-05	2.00E-05		0.91
K-40	D	1.19E-05	1.24E-05	1.20E-05		
Ca-41	W	1.29E-06	1.35E-06	1.30E-06		
Ti-44+D	D	4.18E-04	4.52E-04	4.50E-04	0.92	
V-49	W	3.46E-07	3.45E-07	2.80E-07		0.81
Mn-54	W	6.36E-06	6.70E-06	6.40E-06	0.95	
Fe-55	W	1.36E-06	1.34E-06	1.20E-06		0.90
Fe-60+D	W	na	2.70E-04	2.70E-04		
Co-60	W	3.20E-05	3.31E-05	3.00E-05		0.91
Ni-59	W	9.00E-07	9.18E-07	7.00E-07		0.76
Ni-63	W	2.30E-06	2.30E-06	1.90E-06		0.83
Se-79	D	6.13E-06	6.55E-06	6.20E-06	0.94	0.95
Rb-87	D	3.18E-06	3.23E-06	3.30E-06		
Sr-90+D	D	2.09E-04	2.47E-04	2.37E-04	0.85	
Zr-93	W	8.16E-05	8.33E-05	8.10E-05		
Nb-91	W	2.88E-06	3.21E-06	4.10E-06	0.90	1.28
Nb-93m	W	2.88E-06	3.21E-06	4.10E-06	0.90	1.28
Nb-94	W	3.38E-05	3.61E-05	2.60E-05	0.94	0.72
Mo-93	Y	2.80E-05	2.84E-05	2.80E-05		
Tc-99	W	9.00E-06	8.33E-06	7.50E-06	1.08	0.90
Ru-106+D	W	1.18E-04	1.18E-04	9.30E-05		0.79
Pd-107	Y	1.29E-05	1.28E-05	1.30E-05		
Ag-108m+D	W	2.44E-05	2.53E-05	1.90E-05		0.75
Cd-109	D	1.15E-04	1.14E-04	1.00E-04		0.87
Cd-113m	D	1.54E-03	1.53E-03	1.40E-03		0.92
In-115	D	2.02E-03	3.74E-03	3.40E-03	0.54	0.91
Sn-121m+D	W	1.18E-05	1.19E-05	9.26E-06		0.78
Sn-126+D	W	9.99E-05	1.01E-04	7.54E-05		0.75
Sb-125	W	1.23E-05	1.22E-05	9.80E-06		0.80
Te-125m	W	7.18E-06	7.29E-06	6.70E-06		0.92
I-129	D	1.51E-04	1.74E-04	1.80E-04	0.87	
Cs-134	D	4.28E-05	4.63E-05	4.70E-05	0.93	
Cs-135	D	4.49E-06	4.55E-06	4.50E-06		

Table A22. Inhalation Dose Factors, mrem/pCi Inhaled.

Nuclide	Lung Model	GENII	EPA	DOE	GENII / EPA	DOE / EPA
Cs-137+D	D	2.98E-05	3.19E-05	3.20E-05	0.93	
Ba-133	D	6.00E-06	7.81E-06	6.90E-06	0.77	0.88
Pm-147	Y	3.92E-05	3.92E-05	3.40E-05		0.87
Sm-147	W	7.48E-02	7.47E-02	7.10E-02		0.95
Sm-151	W	3.01E-05	3.00E-05	2.90E-05		
Eu-150	W	2.50E-04	2.68E-04	2.70E-04	0.93	
Eu-152	W	2.11E-04	2.21E-04	2.20E-04		
Eu-154	W	2.78E-04	2.86E-04	2.60E-04		0.91
Eu-155	W	4.12E-05	4.14E-05	3.90E-05		0.94
Gd-152	D	2.44E-01	2.43E-01	2.40E-01		
Ho-166m	W	7.46E-04	7.73E-04	7.20E-04		0.93
Re-187	W	5.86E-08	5.44E-08	4.90E-08	1.08	0.90
Tl-204	D	2.46E-06	2.41E-06	2.30E-06		
Pb-205	D	3.97E-06	3.92E-06	3.70E-06		0.94
Pb-210+D	D	1.37E-02	1.36E-02	1.30E-02		
Bi-207	W	1.96E-05	2.00E-05	1.40E-05		0.70
Po-209	W	1.15E-02	1.07E-02	1.01E-02	1.07	0.94
Po-210	W	8.63E-03	8.58E-03	8.10E-03		0.94
Ra-226+D	W	8.22E-03	8.60E-03	7.91E-03		0.92
Ra-228+D	W	4.18E-03	4.86E-03	4.29E-03	0.86	0.88
Ac-227+D	W	1.74E+00	1.74E+00	1.72E+00		
Th-228+D	Y	3.47E-01	3.42E-01	3.13E-01		0.92
Th-229+D	Y	1.75E+00	1.74E+00	1.72E+00		
Th-230	Y	2.62E-01	2.62E-01	2.60E-01		
Th-232	Y	1.15E+00	1.15E+00	1.10E+00		
Pa-231	W	1.29E+00	1.28E+00	1.30E+00		
U-232	W	1.52E-02	1.49E-02	1.30E-02		0.87
U-233	W	8.01E-03	7.99E-03	7.10E-03		0.89
U-234	W	7.99E-03	7.88E-03	7.10E-03		0.90
U-235+D	W	7.48E-03	7.29E-03	6.70E-03		0.92
U-236	W	7.49E-03	7.44E-03	6.70E-03		0.90
U-238+D	W	7.03E-03	7.06E-03	6.23E-03		0.88
Np-237+D	W	6.32E-01	5.40E-01	4.90E-01	1.17	0.91
Pu-236	W	1.45E-01	1.45E-01	1.60E-01		1.11
Pu-238	W	3.90E-01	3.92E-01	4.60E-01		1.17
Pu-239	W	4.30E-01	4.29E-01	5.10E-01		1.19
Pu-240	W	4.30E-01	4.29E-01	5.10E-01		1.19
Pu-241+D	W	8.17E-03	8.25E-03	1.00E-02		1.21
Pu-242	W	4.08E-01	4.11E-01	4.80E-01		1.17

Table A22. Inhalation Dose Factors, mrem/pCi Inhaled.

Nuclide	Lung Model	GENII	EPA	DOE	GENII / EPA	DOE / EPA
Pu-244+D	W	4.03E-01	4.03E-01	4.80E-01		1.19
Am-241	W	4.41E-01	4.44E-01	5.20E-01		1.17
Am-242m+D	W	4.24E-01	4.26E-01	5.10E-01		1.20
Am-243+D	W	4.41E-01	4.40E-01	5.20E-01		1.18
Cm-242	W	1.75E-02	1.73E-02	1.70E-02		
Cm-243	W	3.07E-01	3.07E-01	3.50E-01		1.14
Cm-244	W	2.48E-01	2.48E-01	2.70E-01		1.09
Cm-245	W	4.55E-01	4.55E-01	5.40E-01		1.19
Cm-246	W	4.51E-01	4.51E-01	5.40E-01		1.20
Cm-247+D	W	4.15E-01	4.14E-01	4.90E-01		1.18
Cm-248	W	1.65E+00	1.65E+00	1.90E+00		1.15
Cm-250+D	W	9.43E+00	9.40E+00	9.40E+00		
Bk-247	W	4.65E-01	5.74E-01	5.50E-01	0.81	
Cf-248	W	4.44E-02	4.44E-02	3.80E-02		0.86
Cf-249	W	5.77E-01	5.77E-01	5.50E-01		
Cf-250	W	2.63E-01	2.62E-01	2.20E-01		0.84
Cf-251	W	5.87E-01	5.88E-01	5.60E-01		
Cf-252	W	1.37E-01	1.37E-01	1.20E-01		0.88

Notes:

- The inhaled particulate is assumed to have an activity median aerodynamic diameter of 1 µm.
- GENII inhalation dose factors are based on the 1993 revision (WHC-SD-WM-TI-596). EPA inhalation dose factors from Federal Guidance Report Number 11, EPA-520/1-88-020, Sept 1988. DOE inhalation dose factors from DOE/EH-0071, (DE88-014297), July 1988. All are 50 year committed EDE.
- "Lung Model" refers to the ICRP 30 lung model classification, "Water" is water vapor (for which the inhalation dose factor has been increased by 50% to include absorption through the skin), "Organic" means organically bound carbon, "D" is days, "W" is weeks, and "Y" is years. The value shown are those recommended in ICRP Report Number 71 for unknown chemical types.
- The short-lived radioactive progeny shown on Table A1 are assumed to be in secular equilibrium with their parent nuclide. The dose factors for implicit daughters have been multiplied by the branching ratios in Table A1 and added to the parent dose factor to give the values shown.
- The last two columns show ratios of GENII and DOE inhalation dose factors to the EPA dose factors. Ratios of dose factors within 5% of the EPA value are not shown.

Table A23. Internal Dose Factors for Adults from ICRP 72, mrem/pCi.

Nuclide	f1	Ingestion	EPA / ICRP 72	Lung Model	Inhalation	EPA / ICRP 72
H-3	1	6.66E-08		M	1.67E-07	0.58
Be-10	0.005	4.07E-06	1.15	S	1.30E-04	2.74
C-14	1	2.15E-06		M	7.40E-06	0.28
Na-22	1	1.18E-05		F	4.81E-06	1.59
Al-26	0.01	1.30E-05	1.13	M	7.40E-05	
Si-32+D	0.01	1.10E-05		S	4.20E-04	2.45
Cl-36	1	3.44E-06	0.88	M	2.70E-05	0.81
K-40	1	2.29E-05	0.81	F	7.77E-06	1.59
Ca-41	0.3	7.03E-07	1.81	M	3.52E-07	3.83
Ti-44+D	0.01	2.28E-05	1.08	F	2.26E-04	2.00
V-49	0.01	6.66E-08	0.92	M	1.26E-07	2.74
Mn-54	0.1	2.63E-06	1.05	M	5.55E-06	1.21
Fe-55	0.1	1.22E-06	0.50	M	1.41E-06	0.95
Fe-60+D	0.1	4.07E-04	0.37	M	5.18E-04	0.52
Co-60	0.1	1.26E-05	2.14	M	3.70E-05	0.89
Ni-59	0.05	2.33E-07	0.90	M	4.81E-07	1.91
Ni-63	0.05	5.55E-07		M	1.78E-06	1.30
Se-79	0.8	1.07E-05	0.81	F	4.07E-06	1.61
Rb-87	1	5.55E-06	0.89	F	1.85E-06	1.75
Sr-90+D	0.3	1.14E-04	1.35	M	1.38E-04	1.79
Zr-93	0.01	4.07E-06	0.41	M	3.70E-05	2.25
Nb-91	0.01	4.44E-07	1.18	M	1.89E-06	1.70
Nb-93m	0.01	4.44E-07	1.18	M	1.89E-06	1.70
Nb-94	0.01	6.29E-06	1.14	M	4.07E-05	0.89
Mo-93	1	1.15E-05	0.12	M	2.18E-06	13.0
Tc-99	0.5	2.37E-06	0.62	M	1.48E-05	0.56
Ru-106+D	0.05	2.59E-05	1.06	M	1.04E-04	1.14
Pd-107	0.005	1.37E-07	1.09	S	2.18E-06	5.85
Ag-108m+D	0.05	8.51E-06	0.90	M	2.74E-05	0.92
Cd-109	0.05	7.40E-06	1.78	F	3.00E-05	3.81
Cd-113m	0.05	8.51E-05	1.89	F	4.07E-04	3.75
In-115	0.02	1.18E-04	1.33	F	1.44E-03	2.59
Sn-121m+D	0.02	2.07E-06	1.09	M	1.73E-05	0.69
Sn-126+D	0.02	1.88E-05	1.12	M	1.05E-04	
Sb-125	0.1	4.07E-06	0.69	M	1.78E-05	0.69
Te-125m	0.3	3.22E-06	1.14	M	1.26E-05	0.58
I-129	1	4.07E-04	0.68	F	1.33E-04	1.30
Cs-134	1	7.03E-05		F	2.44E-05	1.89
Cs-135	1	7.40E-06		F	2.55E-06	1.78

Table A23. Internal Dose Factors for Adults from ICRP 72, mrem/pCi.

Nuclide	f1	Ingestion	EPA / ICRP 72	Lung Model	Inhalation	EPA / ICRP 72
Cs-137+D	1	4.81E-05		F	1.70E-05	1.88
Ba-133	0.2	5.55E-06	0.61	M	1.15E-05	0.68
Pm-147	0.0005	9.62E-07	1.09	S	1.81E-05	2.16
Sm-147	0.0005	1.81E-04		M	3.55E-02	2.10
Sm-151	0.0005	3.63E-07	1.07	M	1.48E-05	2.03
Eu-150	0.0005	4.81E-06	1.32	M	1.96E-04	1.37
Eu-152	0.0005	5.18E-06	1.25	M	1.55E-04	1.42
Eu-154	0.0005	7.40E-06	1.29	M	1.96E-04	1.46
Eu-155	0.0005	1.18E-06	1.29	M	2.55E-05	1.62
Gd-152	0.0005	1.52E-04	1.06	F	7.03E-02	3.46
Ho-166m	0.0005	7.40E-06	1.09	M	4.44E-04	1.74
Re-187	0.8	1.89E-08	0.50	M	2.33E-08	2.33
Tl-204	1	4.44E-06	0.76	F	1.44E-06	1.67
Pb-205	0.2	1.04E-06	1.58	M	9.25E-07	4.24
Pb-210+D	0.2	2.56E-03	2.10	M	4.41E-03	3.08
Bi-207	0.05	4.81E-06	1.14	M	2.07E-05	
Po-209	0.5	5.54E-03	0.43	M	1.52E-02	0.70
Po-210	0.5	4.44E-03	0.43	M	1.22E-02	0.70
Ra-226+D	0.2	1.04E-03	1.28	M	1.31E-02	0.66
Ra-228+D	0.2	2.55E-03	0.56	M	9.68E-03	0.50
Ac-227+D	0.0005	4.47E-03	3.30	M	8.73E-01	2.00
Th-228+D	0.0005	5.31E-04	1.53	S	1.61E-01	2.12
Th-229+D	0.0005	2.27E-03	1.77	S	3.23E-01	5.40
Th-230	0.0005	7.77E-04	0.70	S	5.18E-02	5.05
Th-232	0.0005	8.51E-04	3.21	S	9.25E-02	12.4
Pa-231	0.0005	2.63E-03	4.03	M	5.18E-01	2.48
U-232	0.02	1.22E-03	1.07	M	2.89E-02	0.52
U-233	0.02	1.89E-04	1.53	M	1.33E-02	0.60
U-234	0.02	1.81E-04	1.56	M	1.30E-02	0.61
U-235+D	0.02	1.75E-04	1.53	M	1.15E-02	0.64
U-236	0.02	1.74E-04	1.54	M	1.18E-02	0.63
U-238+D	0.02	1.79E-04	1.50	M	1.08E-02	0.66
Np-237+D	0.0005	4.10E-04	10.8	M	8.51E-02	6.35
Pu-236	0.0005	3.22E-04	3.62	M	7.40E-02	1.96
Pu-238	0.0005	8.51E-04	3.76	M	1.70E-01	2.30
Pu-239	0.0005	9.25E-04	3.82	M	1.85E-01	2.32
Pu-240	0.0005	9.25E-04	3.82	M	1.85E-01	2.32
Pu-241+D	0.0005	1.78E-05	3.85	M	3.33E-03	2.48
Pu-242	0.0005	8.88E-04	3.78	M	1.78E-01	2.31

Table A23. Internal Dose Factors for Adults from ICRP 72, mrem/pCi.

Nuclide	f1	Ingestion	EPA / ICRP 72	Lung Model	Inhalation	EPA / ICRP 72
Pu-244+D	0.0005	8.92E-04	3.73	M	1.74E-01	2.32
Am-241	0.0005	7.40E-04	4.92	M	1.55E-01	2.86
Am-242m+D	0.0005	7.04E-04	4.99	M	1.37E-01	3.11
Am-243+D	0.0005	7.43E-04	4.88	M	1.52E-01	2.90
Cm-242	0.0005	4.44E-05	2.58	M	1.92E-02	0.90
Cm-243	0.0005	5.55E-04	4.53	M	1.15E-01	2.68
Cm-244	0.0005	4.44E-04	4.54	M	9.99E-02	2.48
Cm-245	0.0005	7.77E-04	4.81	M	1.55E-01	2.93
Cm-246	0.0005	7.77E-04	4.76	M	1.55E-01	2.90
Cm-247+D	0.0005	7.03E-04	4.86	M	1.44E-01	2.87
Cm-248	0.0005	2.85E-03	4.78	M	5.55E-01	2.98
Cm-250+D	0.0005	1.63E-02	4.77	M	3.11E+00	3.02
Bk-247	0.0005	1.30E-03	3.63	M	2.55E-01	2.25
Cf-248	0.0005	1.04E-04	3.23	M	3.26E-02	1.36
Cf-249	0.0005	1.30E-03	3.66	M	2.59E-01	2.23
Cf-250	0.0005	5.92E-04	3.60	M	1.26E-01	2.08
Cf-251	0.0005	1.33E-03	3.64	M	2.63E-01	2.24
Cf-252	0.0005	3.33E-04	3.26	M	7.40E-02	1.85

Notes:

- The ingestion and inhalation doses are from ICRP Publication 72 for adults. All are 50 year committed effective dose equivalent. The inhalation dose factors assume the particle size distribution has an activity median aerodynamic diameter of 1 µm.
- "Lung Model" refers to the ICRP 66 lung model classification,"F" is fast, "M" is moderate, and "S" is slow absorption of inhaled particulate material into body fluids.
- The short-lived radioactive progeny shown on Table A1 are assumed to be in secular equilibrium with their parent nuclide. The dose factors for implicit daughters have been multiplied by the branching ratios in Table A1 and added to the parent dose factor to give the values shown.
- The ratios of the EPA dose factors divided by the ICRP 72 dose factors are shown if the difference between them is greater than 5%.

Table A24. Nuclear Decay Data for Nb-91 and Nb-93m.

Nb-91 (680 y)	**Particle energy, keV**	**fraction of decays**	**Weighted energy, keV**
electron capture	1254.6	0.99836	417.51
positron	232.6	0.00164	0.13
electron	13.47	0.2348	3.16
photon	15.69	0.18319	2.87
	15.77	0.35027	5.52
	17.66	0.10136	1.79
	511	0.00328	1.68
		Total for electrons + photons:	15 keV
Nb-93m(16.13 y)	**Particle energy, keV**	**fraction of decays**	**Weighted energy, keV**
isomeric transition	30.77	1	30.77
electron	11.78	0.1440	1.70
	14.15	0.0365	0.52
	28.07	0.1340	3.76
	28.31	0.0262	0.74
	28.40	0.4710	13.38
	30.39	0.1360	4.13
photon	16.52	0.0310	0.51
	16.61	0.0590	0.98
	18.61	0.0175	0.33
	30.77	5.5 E-06	0.00
		Total for electrons + photons:	26 keV

Note: The last column shows the product of the particle energies and the fraction of decays with this energy particle. Although the Nb-93m half-life is short enough that the total retained in the body (and hence the dose) decreases partly by radioactive decay, its total electron plus positron energy is large enough to make up for the loss by decay. Data from ENDF/B-VI.

A3.6 External Dose-Rate Factors for Radionuclides

External dose-rate factors give the expected dose equivalent rate to an individual standing near radioactive contamination. The composition and shape of the contaminated region determines the dose equivalent rates at a given concentration in the medium. Four contaminated regions will be described in this section, a 15-cm soil layer, a large cloud of airborne activity, and at the surface of a body of water. The doses from external exposure with the radioactivity distributed in air or water will be shown to be negligible in comparison to the inhalation or ingestion dose that normally accompanies the external exposure.

A3.6.1 External Dose-Rate Factors for Radionuclides in Surface Soil

The dose rate factors have units of dose equivalent rate per unit area of contaminated soil. The contamination is assumed uniformly spread over a very large area with a thickness of 15 cm (6 in.). If the area becomes smaller than a few hundred square meters, then the dose rate factors must be adjusted downward. The thickness of the contaminated layer affects the dose rate and must be considered. For typical exposure scenarios the soil thickness is 15 cm. Radionuclides are assumed to be uniformly distributed through this thickness as a result of cultivating the soil for the purpose of growing a garden.

External dose rates from a layer of contaminated surface soil are available from various references. Three references that have been used on the Hanford Site are the DOE surface gamma dose-rate conversion factors (DOE/EH-0070), the EPA values in Federal Guidance Report Number 12 (EPA-402-R-93-081), and the external dose factors recently computed for the GENII program. The three sets of external dose rate factors are shown in Table A25. They have been converted to the common units of mrem/hour per Ci/m^2 for purposes of comparison.

The DOE surface gamma conversion factors (DOE/EH-0070) are derived from an assumed contamination thickness of zero. The contamination lies on top of the soil surface in a layer that is infinitely thin, perfectly flat, and infinite in extent. These assumptions necessarily exaggerate the dose rates. Strong beta-emitting nuclides such as Sr-90 produce no external dose since the bremsstrahlung radiation was ignored.

The GENII external dose rate factors (PNNL-6584) were computed using a version of the ISOSHLD program known as EXTDF, which is part of the GENII software package. Bremsstrahlung radiation is computed for all beta emitters. The dose rate factors are calculated 1 m above a contamination thickness of 0.05 m and 0.15 m. The surface soil is given a density of 1.5 grams per cubic centimeter. Again the surface layer is perfectly flat and infinite in extent. The finite thickness adds realism, since the contamination thickness assumed for the well-driller (0.05 m) is increased to 0.15 m during normal tilling operations that are part of the post-drilling scenarios. The 0.15-m dose rate factors have been used in prior Hanford Site performance assessments.

Table A25. External Dose Rate Factors, mrem/h per Ci/m^2.

Nuclide	GENII using EXTDF		EPA Federal Guidance Report Number 12		DOE	GENII / EPA (0.15 m)	DOE / EPA (0.15 m)
	5 cm	15 cm	5 cm	15 cm			
H-3	1.05E-07	3.49E-08	0	0	0	EPA=0	
Be-10	1.06E+00	4.33E-01	1.26E+00	5.37E-01	0	0.806	DOE=0
C-14	2.16E-02	7.51E-03	1.92E-02	6.82E-03	0		DOE=0
Na-22	1.22E+04	6.75E+03	1.12E+04	5.98E+03	2.40E+04	1.13	4.01
Al-26	1.60E+04	9.15E+03	1.35E+04	7.32E+03	2.85E+04	1.25	3.89
Si-32+D	2.03E+01	9.62E+00	1.22E+01	5.70E+00	0	1.69	DOE=0
Cl-36	2.03E+00	8.58E-01	2.52E+00	1.16E+00	5.32E-04	0.74	0.000459
K-40	8.61E+02	4.87E+02	7.90E+02	4.33E+02	1.56E+03	1.12	3.6
Ca-41	0	0	0	0	8.60E-01		EPA=0
Ti-44+D	1.30E+04	7.10E+03	1.15E+04	6.00E+03	2.57E+04	1.18	4.28
V-49	0	0	0	0	8.60E-01		EPA=0
Mn-54	4.64E+03	2.53E+03	4.29E+03	2.27E+03	9.59E+03	1.11	4.22
Fe-55	3.22E-01	1.07E-01	0	0	2.52E+00	EPA=0	EPA=0
Fe-60+D	1.91E+01	1.02E+01	2.05E+01	1.05E+01	5.38E+01		5.13
Co-60	1.34E+04	7.51E+03	1.26E+04	6.87E+03	2.59E+04		3.77
Ni-59	3.92E-01	1.31E-01	0	0	4.75E+00	EPA=0	EPA=0
Ni-63	5.72E-04	1.91E-04	0	0	0	EPA=0	
Se-79	1.55E-02	5.37E-03	2.64E-02	9.44E-03	0	0.569	DOE=0
Rb-87	1.08E-01	4.02E-02	1.84E-01	7.13E-02	0	0.564	DOE=0
Sr-90+D	4.08E+01	1.97E+01	2.45E+01	1.17E+01	0	1.68	DOE=0
Zr-93	4.02E-04	1.34E-04	0	0	0	EPA=0	
Nb-91	1.09E+01	5.74E+00	1.09E+01	5.74E+00	8.36E+01		18.6
Nb-93m	1.30E-01	4.33E-02	1.58E-01	5.28E-02	1.17E+01	0.82	222
Nb-94	8.61E+03	4.67E+03	8.13E+03	4.29E+03	1.81E+04		4.22
Mo-93	7.28E-01	2.43E-01	8.98E-01	2.99E-01	6.59E+01	0.813	220
Tc-99	1.35E-01	5.04E-02	1.63E-01	6.35E-02	7.14E-03	0.794	0.112
Ru-106+D	1.36E+03	7.32E+02	1.12E+03	5.83E+02	2.40E+03	1.26	4.12
Pd-107	1.25E-05	4.16E-06	0	0	0	EPA=0	
Ag-108m+D	1.00E+04	5.37E+03	8.39E+03	4.37E+03	1.90E+04	1.23	4.35
Cd-109	2.13E+01	2.61E+00	1.95E+01	7.47E+00	1.08E+02	0.349	14.5
Cd-113m	1.05E+00	4.28E-01	7.70E-01	3.24E-01	0	1.32	DOE=0
In-115	6.38E-01	2.56E-01	4.89E-01	2.01E-01	0	1.27	DOE=0
Sn-121m+D	1.54E+01	5.15E+00	3.18E+00	1.07E+00	0	4.81	DOE=0
Sn-126+D	1.22E+04	6.56E+03	1.03E+04	5.36E+03	2.37E+04	1.22	4.42
Sb-125	1.73E+03	1.49E+03	2.18E+03	1.12E+03	5.05E+03	1.33	4.51
Te-125m	2.58E+01	8.78E+00	2.27E+01	7.67E+00	2.40E+02	1.14	31.3
I-129	1.66E+01	5.54E+00	1.97E+01	6.57E+00	2.51E+02	0.843	38.2
Cs-134	9.71E+03	5.23E+03	8.04E+03	4.24E+03	1.80E+04	1.23	4.25
Cs-135	4.09E-02	1.46E-02	5.26E-02	1.94E-02	0	0.753	DOE=0
Cs-137+D	3.39E+03	1.82E+03	2.93E+03	1.53E+03	6.58E+03	1.19	4.3
Ba-133	2.16E+03	1.10E+03	1.89E+03	9.36E+02	4.78E+03	1.18	5.11
Pm-147	7.30E-02	2.74E-02	6.51E-02	2.53E-02	4.68E-02		1.85
Sm-147	0	0	0	0	0		
Sm-151	5.85E-03	1.95E-03	1.50E-03	4.99E-04	5.93E-02	3.91	119
Eu-150	9.37E+03	5.04E+03	7.65E+03	3.96E+03	0	1.27	DOE=0

Table A25. External Dose Rate Factors, mrem/h per Ci/m^2.

Nuclide	GENII using EXTDF		EPA Federal Guidance Report Number 12		DOE	GENII / EPA (0.15 m)	DOE / EPA (0.15 m)
	5 cm	15 cm	5 cm	15 cm			
Eu-152	6.53E+03	3.60E+03	5.77E+03	3.05E+03	1.27E+04	1.18	4.16
Eu-154	6.80E+03	3.74E+03	6.28E+03	3.34E+03	1.38E+04	1.12	4.13
Eu-155	2.19E+02	8.98E+01	2.26E+02	9.24E+01	8.16E+02		8.83
Gd-152	0	0	0	0	0		
Ho-166m	8.78E+03	4.67E+03	8.95E+03	4.64E+03	1.88E+04		4.05
Re-187	0	0	0	0	0		
Tl-204	4.85E+00	1.93E+00	5.14E+00	2.04E+00	1.48E+01		7.25
Pb-205	2.63E-01	8.75E-02	1.07E-02	3.58E-03	8.61E+00	24.4	2410
Pb-210+D	9.36E+00	3.85E+00	7.59E+00	3.00E+00	3.42E+01	1.28	11.4
Bi-207	8.95E+03	4.92E+03	7.79E+03	4.11E+03	1.72E+04	1.2	4.18
Po-209	1.72E+01	8.95E+00	1.72E+01	8.95E+00	4.10E+01		4.6
Po-210	4.92E-02	2.68E-02	4.38E-02	2.32E-02	9.81E-02	1.16	4.23
Ra-226+D	1.01E+04	5.61E+03	8.92E+03	4.78E+03	1.92E+04	1.17	4.02
Ra-228+D	5.49E+03	3.04E+03	4.92E+03	2.62E+03	1.04E+04	1.16	3.97
Ac-227+D	2.16E+03	1.08E+03	1.96E+03	9.61E+02	5.00E+03	1.12	5.2
Th-228+D	8.65E+03	4.92E+03	7.69E+03	4.20E+03	1.66E+04	1.17	3.95
Th-229+D	1.78E+03	9.04E+02	1.52E+03	7.45E+02	4.09E+03	1.21	5.49
Th-230	1.06E+00	4.11E-01	1.48E+00	6.05E-01	1.03E+01	0.679	17
Th-232	5.61E-01	2.13E-01	6.71E-01	2.63E-01	7.60E+00	0.81	28.9
Pa-231	1.80E+02	9.09E+01	1.84E+02	9.11E+01	4.08E+02		4.48
U-232	7.99E-01	3.10E-01	1.10E+00	4.52E-01	1.17E+01	0.686	25.9
U-233	1.13E+00	4.81E-01	1.51E+00	6.86E-01	5.70E+00	0.701	8.31
U-234	4.93E-01	1.89E-01	5.17E-01	2.03E-01	9.21E+00		45.4
U-235+D	5.84E+02	2.52E+02	7.98E+02	3.74E+02	2.17E+03	0.674	5.8
U-236	2.81E-01	9.85E-02	2.87E-01	1.08E-01	8.36E+00		77.4
U-238+D	1.39E+02	7.10E+01	1.20E+02	5.87E+01	2.81E+02	1.21	4.79
Np-237+D	1.41E+03	7.13E+02	1.09E+03	5.28E+02	3.06E+03	1.35	5.8
Pu-236	2.74E-01	9.45E-02	3.13E-01	1.14E-01	1.13E+01	0.829	99.1
Pu-238	3.10E-01	1.06E-01	2.16E-01	7.65E-02	9.79E+00	1.39	128
Pu-239	3.51E-01	1.59E-01	3.27E-01	1.44E-01	4.31E+00	1.1	29.9
Pu-240	2.05E-01	7.29E-02	2.11E-01	7.43E-02	9.35E+00		126
Pu-241+D	2.13E-02	9.43E-03	2.10E-02	9.29E-03	4.40E-02		4.74
Pu-242	2.73E-01	9.57E-02	1.83E-01	6.49E-02	7.78E+00	1.47	120
Pu-244+D	2.18E+03	1.17E+03	1.72E+03	9.04E+02	3.86E+03	1.29	4.27
Am-241	4.18E+01	1.45E+01	6.20E+01	2.22E+01	3.41E+02	0.653	15.4
Am-242m+D	7.98E+01	3.58E+01	7.33E+01	3.28E+01	2.66E+02		8.11
Am-243+D	1.01E+03	4.49E+02	9.80E+02	4.42E+02	2.94E+03		6.65
Cm-242	1.76E-01	5.97E-02	2.44E-01	8.59E-02	1.07E+01	0.695	125
Cm-243	6.34E+02	2.90E+02	6.08E+02	2.86E+02	1.67E+03		5.84
Cm-244	1.51E-01	5.09E-02	1.92E-01	6.39E-02	9.46E+00	0.797	148
Cm-245	3.11E+02	1.32E+02	3.89E+02	1.71E+02	9.74E+02	0.772	5.7
Cm-246	1.26E-01	4.19E-02	1.77E-01	5.89E-02	8.37E+00	0.711	142
Cm-247+D	2.44E+03	1.30E+03	1.74E+03	8.74E+02	4.16E+03	1.49	4.76
Cm-248	1.13E-01	3.83E-02	1.34E-01	4.45E-02	6.71E+00	0.861	151
Cm-250+D	2.17E+03	1.20E+03	1.65E+03	8.55E+02	4.40E+03	1.4	5.15

Table A25. External Dose Rate Factors, mrem/h per Ci/m^2.

Nuclide	GENII using EXTDF		EPA Federal Guidance Report Number 12		DOE	GENII / EPA (0.15 m)	DOE / EPA (0.15 m)
	5 cm	15 cm	5 cm	15 cm			
Bk-247	5.01E+02	2.32E+02	4.72E+02	2.14E+02	0		DOE=0
Cf-248	1.03E-01	3.43E-02	1.90E-01	6.32E-02	7.68E+00	0.543	122
Cf-249	1.89E+03	9.82E+02	1.72E+03	8.71E+02	4.02E+03	1.13	4.62
Cf-250	1.53E-01	5.37E-02	1.80E-01	6.01E-02	7.81E+00	0.894	130
Cf-251	5.46E+02	2.40E+02	5.68E+02	2.62E+02	1.55E+03		5.92
Cf-252	1.24E-01	4.25E-02	2.46E-01	8.91E-02	7.23E+00	0.477	81.1

Notes:
- GENII external dose rate factors were computed using the EXTDF program. EPA external dose rate factors are from Federal Guidance Report Number 12, EPA 402-R-93-081 (Sept 1993). DOE external dose rate factors are from DOE/EH-0070 (July 1988).
- Short-lived radioactive progeny included in the "+D" nuclides are in secular equilibrium with their parent nuclide.
- The conversion to area units from volume units assumes a thickness of 0.05 m or 0.15 m. The density correction applied to the EPA (1993) dose rate factors is 1.067. Because Nb-91 and Po-209 are not part of the EPA compilation, the GENII values were used.
- The last two columns show ratios of GENII (0.15 m) and DOE external dose rate factors to the EPA (0.15 m) dose rate factors. Ratios within 10% of the EPA value are not shown.

The EPA external dose rate factors (EPA-402-R-93-081) were computed using a Monte Carlo approach with the best available input data and dosimetric models, except that ICRP 30 organ weighting factors rather than ICRP 60 weighting factors were used. The EPA external dose rate factors also include exposure to the skin using a weighting factor of 0.01. These are considered to be the best external dose rate factors currently available and will be used in the tank waste PA. The EPA values shown in Table A25 are for a soil contamination thickness of 5 cm and 15 cm. The number shown for Eu-150 is listed as Eu-150b in the EPA compilation. The reference does not give values for Nb-91 and Po-210. Therefore, the values computed by EXTDF were used instead.

The GENII and EPA external dose rate factors are available as dose rate per unit concentration in the soil. The unit concentration was converted to a unit area by multiplying by the contamination thickness. The DOE dose rate factors are already in area units. Note that the EPA dose rate factors were developed for a soil density of 1.6 g/cc. However, the tank waste PA will use a soil density for the surface layer of 1.5 g/cc. Therefore, the EPA dose rate factors were multiplied by the ratio of densities (1.067) to give the values shown on Table A25.

The three external dose factor collections are compared in Table A25. What is shown on this table are ratios of the GENII (15 cm) and DOE collections divided by the EPA (15 cm) collection. Differences less than 10 percent are not shown. Ratios for dose rate factors that are zero were not computed.

The GENII external dose rate factors agree fairly well (within 26%) for nuclides that emit penetrating gamma rays and have the largest dose rate factors. Examples are Na-22, Al-26, Ti-44, Mn-54, Fe-60, Co-60, Nb-94, Ag-108m, Sn-126, Cs-134, Cs-137, Eu-150, Eu-152, Eu-154, Ho-166m, Bi-207, Ra-226, Ra-228, and Th-228. The disagreement between GENII and the EPA collections is over the low energy photon emitters. However, for these nuclides the internal doses are typically much greater than the external, so the different external dose rate factors would not affect the total doses.

In general, the DOE external dose rate factors are larger than the 15-cm EPA dose rate factors by more than a factor of 4. The exceptions (Be-10, C-14, Si-32, Cl-36, Se-79, Rb-87, Sr-90, Tc-99, Cd-113m, In-115, Sn-121m, Cs-135, and Pm-147) are for nuclides, which produce most of their photons through bremsstrahlung. For these nuclides, the DOE external dose rate factors are much too small. The 5-cm EPA dose rate factors are closer to DOE numbers due to the thinner source.

In all three references used in Table A25 the dose rates were computed at a height of 1 meter above the soil. The actual height has little effect on the dose rate. Table A26 demonstrates this by comparing dose rate factors computed by the EXTDF program at 100 cm and 10 cm. The table shows the ratios of the 10 cm dose rate divided by the 100 cm dose rate for nuclides where the difference between dose rate factors was greater than 10 percent. It must be noted that all these nuclides have external dose rates that are insignificant compared with the internal. The exclusively low energy photons emitted by these nuclides are noticeably attenuated by the additional 90 cm of air.

Table A26. Ratios of Dose Rate Factors at Two Elevations.

Nuclide	Ratio		Nuclide	Ratio
H-3	1.61		U-236	1.26
Fe-55	1.61		Pu-236	1.35
Ni-59	1.18		Pu-238	1.27
Ni-63	1.18		Pu-240	1.37
Zr-93	1.20		Pu-242	1.46
Nb-93m	1.61		Cm-242	1.46
Mo-93	1.61		Cm-244	1.48
Pd-107	1.52		Cm-246	1.52
Sm-151	1.21		Cm-248	1.46
Pb-205	1.61		Cf-248	1.55
Th-232	1.12		Cf-250	1.36
U-232	1.13		Cf-252	1.42
U-234	1.16			

Notes:
- The ratios are the dose rate factor (DRF) at 10 cm above the soil surface divided by the dose rate factor at 1 meter above the soil. Both DRFs are from EXTDF.
- Nuclides having DRFs within 10% at the two elevations are not shown.

Some of the external exposure pathways noted in Table 3 for the low water infiltration case are much smaller than internal pathways that accompany the external exposure. For example, the external exposure to an individual whose livestock drinks contaminated well water is much smaller than the internal dose resulting from the consumption of the animal products (milk, meat, poultry, and eggs). This follows from the observation that the dose resulting from a given amount of radioactivity outside the body (leading to an external dose) is orders of magnitude lower than the dose resulting from the same amount of radioactivity ingested or inhaled (leading to an internal dose). Admittedly, the individual will not eat all of the radioactivity present in an animal, since the radioactivity will be present in organs and tissues that are not normally eaten. However, the use of all four animal pathways combined with the observation that the individual is in close proximity to the animal for only short periods during the day gives assurance that this external pathway can be ignored.

A3.6.2 External Dose-Rate Factors for Radionuclides in Air

External dose rate factors for immersion in contaminated air are listed in Table A27. Values are from Federal Guidance Report Number 12 (EPA-402-R-93-081). The dose rate factors were computed assuming the individual is located at the center of a hemisphere of infinite extent. Hence these are also referred to as semi-infinite cloud dose rate factors. Values for Nb-91 and Po-209 are from the EXTDF program of the GENII software package.

The columns labeled "Ratio" compare the external dose from submersion in contaminated air with the typical inhalation dose that accrues during the same period. The inhalation dose is computed as the product of the air concentration, the exposure time, the breathing rate (0.95 m^3/h), and the inhalation dose factor (Table A22). The submersion dose is computed as the product of the air concentration, the exposure time, and the submersion dose rate factor. Thus the ratio of inhalation dose to submersion dose is the product of the breathing rate and the inhalation dose factor divided by the air submersion dose rate factor. This ratio is shown in Table A27. The light activity-breathing rate could also be used, but leads to larger ratios.

For the nuclides used in this report (Table A1), the smallest ratio is 5.06 for Na-22. This is the only isotope with a ratio smaller than 10. In any exposure scenario involving Na-22 there is additional external exposure from soil contamination and ingestion doses. Thus the submersion dose is a minor contributor to the overall total dose.

In Table A27, nuclides notable for large inhalation doses, like insoluble transuranic (TRU) isotopes, have ratios greater than 1 million. Because the activity inhaled by the individual is considerably smaller than the activity ingested, the inhalation dose for non-TRU isotopes is a small part of the total. Therefore, the air submersion dose from airborne particulate will not be included in the dose calculations.

Table A27. External Dose Rate Factors for Air, mrem/h per pCi/m^3.

Nuclide	Air DRF	Ratio	Nuclide	Air DRF	Ratio
H-3	4.41E-12	2.07E+04	Pb-210+D	1.19E-09	1.09E+07
Be-10	1.49E-10	2.26E+06	Bi-207	1.00E-06	1.89E+01
C-14	2.98E-12	6.64E+05	Po-209	2.43E-09	4.19E+06
Na-22	1.44E-06	5.06E+00	Po-210	5.54E-12	1.47E+09
Al-26	1.81E-06	3.78E+01	Ra-226+D	1.18E-06	6.92E+03
Si-32+D	1.33E-09	7.38E+05	Ra-228+D	6.37E-07	7.26E+03
Cl-36	2.97E-10	7.02E+04	Ac-227+D	2.47E-07	6.70E+06
K-40	1.07E-07	1.09E+02	Th-228+D	1.08E-06	3.02E+05
Ti-44+D	1.47E-06	2.92E+02	Th-229+D	1.98E-07	8.38E+06
Mn-54	5.45E-07	1.17E+01	Th-230	2.32E-10	1.07E+09
Fe-60+D	2.89E-09	8.88E+04	Th-232	1.16E-10	9.41E+09
Co-60	1.68E-06	1.87E+01	Pa-231	2.29E-08	5.32E+07
Se-79	4.04E-12	1.54E+06	U-232	1.89E-10	7.47E+07

Table A27. External Dose Rate Factors for Air, mrem/h per pCi/m^3.

Nuclide	Air DRF	Ratio	Nuclide	Air DRF	Ratio
Rb-87	2.42E-11	1.27E+05	U-233	2.17E-10	3.50E+07
Sr-90+D	2.63E-09	8.93E+04	U-234	1.02E-10	7.37E+07
Nb-91	2.05E-09	1.49E+03	U-235+D	1.03E-07	6.73E+04
Nb-93m	5.91E-11	5.16E+04	U-236	6.67E-11	1.06E+08
Nb-94	1.03E-06	3.34E+01	U-238+D	1.57E-08	4.26E+05
Mo-93	3.36E-10	8.04E+04	Np-237+D	1.38E-07	3.71E+06
Tc-99	2.16E-11	3.67E+05	Pu-236	8.46E-11	1.62E+09
Ru-106+D	1.39E-07	8.07E+02	Pu-238	6.50E-11	5.73E+09
Ag-108m+D	1.04E-06	2.31E+01	Pu-239	5.65E-11	7.22E+09
Cd-109	3.92E-09	2.77E+04	Pu-240	6.33E-11	6.44E+09
Cd-113m	9.24E-11	1.57E+07	Pu-241+D	2.87E-12	2.73E+09
In-115	5.99E-11	5.92E+07	Pu-242	5.34E-11	7.30E+09
Sn-121m+D	8.26E-10	1.37E+04	Pu-244+D	2.17E-07	1.76E+06
Sn-126+D	1.28E-06	7.50E+01	Am-241	1.09E-08	3.87E+07
Sb-125	2.69E-07	4.31E+01	Am-242m+D	1.02E-08	3.96E+07
Te-125m	6.03E-09	1.15E+03	Am-243+D	1.31E-07	3.18E+06
I-129	5.06E-09	3.26E+04	Cm-242	7.58E-11	2.17E+08
Cs-134	1.01E-06	4.36E+01	Cm-243	7.83E-08	3.72E+06
Cs-135	7.53E-12	5.74E+05	Cm-244	6.54E-11	3.60E+09
Cs-137+D	3.62E-07	8.37E+01	Cm-245	5.27E-08	8.20E+06
Ba-133	2.37E-07	3.13E+01	Cm-246	5.94E-11	7.22E+09
Pm-147	9.23E-12	4.04E+06	Cm-247+D	2.14E-07	1.84E+06
Sm-151	4.81E-13	5.92E+07	Cm-248	4.52E-11	3.48E+10
Eu-150	9.55E-07	2.67E+02	Cm-250+D	2.11E-07	4.23E+07
Eu-152	7.53E-07	2.79E+02	Bk-247	6.27E-08	8.68E+06
Eu-154	8.18E-07	3.32E+02	Cf-248	6.30E-11	6.69E+08
Eu-155	3.32E-08	1.19E+03	Cf-249	2.10E-07	2.61E+06
Ho-166m	1.13E-06	6.53E+02	Cf-250	5.99E-11	4.15E+09
Tl-204	7.45E-10	3.07E+03	Cf-251	7.43E-08	7.52E+06
Pb-205	6.74E-12	5.53E+05	Cf-252	6.74E-11	1.93E+09

Notes:

- External dose rate factors (DRF) for submersion in contaminated air are from Federal Guidance Report Number 12, EPA 402-R-93-081 (Sept 1993). Because Nb-91 and Po-209 are not part of the EPA compilation, the GENII values were used. Short-lived radioactive progeny included in the "+D" nuclides are in secular equilibrium with their parent nuclide. The nuclide is dispersed uniformly in a hemisphere of infinite extent. The receptor is at the center of the hemisphere. The following were omitted from the table because the DRF is zero: Ca-41, V-49, Fe-55, Ni-59, Ni-63, Sm-147, Gd-152, and Re-187.
- The "Ratio" columns compare the inhalation dose to the external dose. The ratio is computed as the inhalation dose factor times the daily average breathing rate (0.95 m^3/h) divided by the submersion dose rate factor.

A3.6.3 External Dose-Rate Factors for Radionuclides in Water

External dose rate factors for immersion in contaminated water are from Federal Guidance Report Number 12 (EPA-402-R-93-081). The dose rate factors in this reference were computed assuming the individual is located at the center of a sphere of infinite extent. Hence these are also referred to as infinite medium dose rate factors. Values for Nb-91 and Po-209 are from the EXTDF program of the GENII software package.

The EPA values have been converted from Sv/s per Bq/m^3 for an infinite medium to mrem/h per pCi/L for a semi-infinite medium. These are listed in Table A28. The semi-infinite medium corresponds to the dose rate at the surface of a body of water. It may include swimming or shoreline activities. The relationship between infinite medium dose rate factors and semi-infinite medium dose rate factors is simply a factor of two.

The columns labeled "Ratio" compare the external dose from swimming in contaminated water with the ingestion dose from drinking water. The doses are calculated according to the usage parameters for the recreational scenario given in the HSRAM Rev 3. The daily ingestion dose is computed as the product of the water concentration, the volume consumed (2 L/d), and the ingestion dose factor (Table A21). The surface water dose is computed as the product of the water concentration, the exposure time (2.6 h/d), and the dose rate factor (Table A28). Thus the ratio of ingestion dose to external dose is the ingestion dose factor times 2/2.6=0.769 L/h divided by the surface water dose rate factor. This ratio is shown in Table A28.

Table A28. External Dose Rate Factors for Water, mrem/h per pCi/L.

Nuclide	Water DRF	Ratio	Nuclide	Water DRF	Ratio
H-3	0.00E+00	0.00E+00	Pb-210+D	1.29E-09	3.19E+06
Be-10	1.45E-10	2.48E+04	Bi-207	1.09E-06	3.86E+00
C-14	2.92E-12	5.49E+05	Po-209	2.90E-09	6.30E+05
Na-22	1.57E-06	5.64E+00	Po-210	6.01E-12	2.43E+08
Al-26	1.96E-06	5.73E+00	Ra-226+D	1.28E-06	7.95E+02
Si-32+D	1.27E-09	6.62E+03	Ra-228+D	6.93E-07	1.60E+03
Cl-36	2.98E-10	7.80E+03	Ac-227+D	2.71E-07	4.18E+04
K-40	1.16E-07	1.23E+02	Th-228+D	1.17E-06	5.33E+02
Ti-44+D	1.60E-06	1.18E+01	Th-229+D	2.17E-07	1.42E+04
Mn-54	5.91E-07	3.60E+00	Th-230	2.62E-10	1.61E+06
Fe-60+D	3.16E-09	3.71E+04	Th-232	1.33E-10	1.58E+07
Co-60	1.82E-06	1.14E+01	Pa-231	2.52E-08	3.23E+05
Se-79	3.95E-12	1.69E+06	U-232	2.14E-10	4.70E+06
Rb-87	2.36E-11	1.61E+05	U-233	2.42E-10	9.17E+05
Sr-90+D	2.51E-09	4.69E+04	U-234	1.17E-10	1.87E+06
Nb-91	2.68E-09	1.49E+02	U-235+D	1.14E-07	1.81E+03
Nb-93m	6.93E-11	5.79E+03	U-236	7.73E-11	2.67E+06
Nb-94	1.11E-06	4.94E+00	U-238+D	1.70E-08	1.21E+04
Mo-93	3.94E-10	2.63E+03	Np-237+D	1.52E-07	2.25E+04
Tc-99	2.09E-11	5.38E+04	Pu-236	9.86E-11	9.10E+06
Ru-106+D	1.49E-07	1.41E+02	Pu-238	7.59E-11	3.24E+07

Table A28. External Dose Rate Factors for Water, mrem/h per pCi/L.

Nuclide	Water DRF	Ratio	Nuclide	Water DRF	Ratio
Ag-108m+D	1.13E-06	5.20E+00	Pu-239	6.39E-11	4.26E+07
Cd-109	4.51E-09	2.24E+03	Pu-240	7.39E-11	3.68E+07
Cd-113m	8.92E-11	1.39E+06	Pu-241+D	3.20E-12	1.65E+07
In-115	5.79E-11	2.09E+06	Pu-242	6.23E-11	4.15E+07
Sn-121m+D	9.63E-10	1.80E+03	Pu-244+D	2.35E-07	1.09E+04
Sn-126+D	1.40E-06	1.16E+01	Am-241	1.25E-08	2.24E+05
Sb-125	2.92E-07	7.39E+00	Am-242m+D	1.14E-08	2.37E+05
Te-125m	7.06E-09	4.00E+02	Am-243+D	1.46E-07	1.91E+04
I-129	5.93E-09	3.58E+04	Cm-242	8.86E-11	9.96E+05
Cs-134	1.09E-06	5.16E+01	Cm-243	8.66E-08	2.23E+04
Cs-135	7.33E-12	7.42E+05	Cm-244	7.66E-11	2.03E+07
Cs-137+D	3.94E-07	9.76E+01	Cm-245	5.89E-08	4.88E+04
Ba-133	2.60E-07	1.00E+01	Cm-246	6.99E-11	4.07E+07
Pm-147	9.32E-12	8.64E+04	Cm-247+D	2.33E-07	1.13E+04
Sm-151	5.66E-13	5.28E+05	Cm-248	5.30E-11	1.98E+08
Eu-150	1.04E-06	4.71E+00	Cm-250+D	2.30E-07	2.60E+05
Eu-152	8.19E-07	6.08E+00	Bk-247	6.99E-08	5.17E+04
Eu-154	8.86E-07	8.29E+00	Cf-248	7.39E-11	3.48E+06
Eu-155	3.74E-08	3.15E+01	Cf-249	2.30E-07	1.59E+04
Ho-166m	1.23E-06	5.06E+00	Cf-250	7.06E-11	2.32E+07
Tl-204	8.13E-10	3.18E+03	Cf-251	8.26E-08	4.51E+04
Pb-205	7.79E-12	1.61E+05	Cf-252	7.86E-11	1.06E+07

Notes:

- External dose rate factors (DRF) for submersion in contaminated water are from Federal Guidance Report Number 12, EPA 402-R-93-081 (Sept 1993). Because Nb-91 and Po-209 are not part of the EPA compilation, the GENII values were used. Short-lived radioactive progeny included in the "+D" nuclides are in secular equilibrium with their parent nuclide. The nuclide is dispersed uniformly in a hemisphere of infinite extent. The receptor is at the center of the hemisphere. The following were omitted from the table because the DRF is zero: Ca-41, V-49, Fe-55, Ni-59, Ni-63, Sm-147, Gd-152, and Re-187.
- The "Ratio" columns compare the ingestion dose to the external dose for the HSRAM recreational scenario. The ratio is computed as the ingestion dose factor times 0.769 L/h divided by the water submersion dose rate factor.

For the nuclides used in this report (Table A1), the smallest ratio is 3.6 for Mn-54. Nuclides with ratios less than 10 are Mn-54, Bi-207, Eu-150, Nb-94, Ho-166m, Ag-108m+D, Na-22, Eu-152, Sb-125, and Eu-154. Each of these also has dose contributions from other pathways (mainly external) that are about the same size as the drinking water ingestion dose. Thus, the largest increase in the recreational scenario first year total dose is 14% for Mn-54. The water submersion dose increases by less than 10% for all other radionuclides being considered. This is a small enough increase it can be ignored. The recreational scenario using ground water was chosen to maximize the effect of the water submersion dose on the total dose. All other scenarios have other pathways or increased ingestion dose which makes the water submersion contribution even less important.

Nuclides notable for large ingestion doses, such as the transuranic (TRU) isotopes, have ratios greater than 100,000. Thus, the water surface external dose will not be included in the dose calculations. It should be noted that Federal Guidance Report Number 13 does not provide unit risk factors for submersion in water.

A3.7 Cancer Morbidity Risk Coefficients for Radionuclides

The HSRAM exposure scenarios are used to determine the potential lifetime intakes of hazardous materials left in the waste. The toxicity of those intakes depends on the chemical and nuclear characteristics of the material. Of primary interest is the risk to the exposed individual of developing some type of cancer, whether or not the cancer is fatal. For radionuclides, the recommended cancer morbidity risk coefficients are found in Federal Guidance Report Number 13 (EPA-402-R-99-001).

Federal Guidance Report 13 provides both mortality (death from cancer) and morbidity (cancer induction) risk coefficients for an average member of the population. The risk is averaged over the age and gender distributions of a group of people whose survival fraction and cancer induction rates are based on recent data for the United States. While these do change with time, they will nevertheless be used to estimate cancer induction risks to persons exposed hundred of years in the future. The risk coefficients can be used for short duration exposures to an entire population, or to lifetime exposures of one individual.

For the radionuclides of interest in this report, the cancer morbidity risk coefficients are shown in Table A29 and A30. The GI absorption fractions and lung clearance types assumed previously are used here. Note that the ingestion and inhalation risk coefficients for Nb-91, Po-209, Cm-248, Cm-250, and Cf-252 were not given in Federal Guidance Report Number 13. Values for these were estimated from other nuclides with risk coefficients.

The ingestion and inhalation risk coefficients for Nb-91 are assumed bounded by those for Nb-93m. The external risk coefficient is calculated from the external risk coefficient for Nb-93m and the GENII external DRFs for Nb-91 and Nb-93m shown in Table A25 using a simple proportionality, as shown below. In the equation below, “SF” refers to the morbidity risk coefficient.

$$
\begin{aligned}
\mathrm{SF}\left({}^{91}\mathrm{Nb}\right) &= \frac{\mathrm{DRF}\left({}^{91}\mathrm{Nb}\right)}{\mathrm{DRF}\left({}^{93m}\mathrm{Nb}\right)}\mathrm{SF}\left({}^{93m}\mathrm{Nb}\right) \\
&= \frac{5.74\ \text{mrem/h per Ci/m}^2}{0.0433\ \text{mrem/h per Ci/m}^2}\left(3.83\text{x}10^{-11}\ \text{risk/y per pCi/g}\right) \\
&= 5.07\text{x}10^{-9}\ \text{risk/y per pCi/g}
\end{aligned}
$$

In a similar manner, the ingestion and inhalation risk coefficients for Po-209 are calculated from the risk coefficients for Po-210 using the constant of proportionality, 1.247, derived in Section A3.5. The external risk coefficient is calculated from the external risk coefficient for Po-210 and the GENII external DRFs for Po-209 and Po-210 shown in Table A25 using a simple proportionality, as shown below.

$$
\begin{aligned}
SF\left({}^{209}Po\right) &= \frac{DRF\left({}^{209}Po\right)}{DRF\left({}^{210}Po\right)} SF\left({}^{210}Po\right) \\
&= \frac{8.95 \text{ mrem/h per Ci/m}^2}{0.0268 \text{ mrem/h per Ci/m}^2}\left(3.95x10^{-11} \text{ risk/y per pCi/g}\right) \\
&= 1.32x10^{-8} \text{ risk/y per pCi/g}
\end{aligned}
$$

Finally, the ingestion and inhalation risk coefficients for Cm-248, Cm-250, and Cf-252 are calculated from the risk coefficients for Cm-246, Cm-246, and Cf-250, respectively. The ratios between internal dose factors from ICRP 72 shown in Table A23 are used for this purpose. These surrogates were chosen because they have alpha particle energies that are roughly the same. The average alpha particle energies for Cm-246, Cm-248, and Cm-250 are 5,377 MeV, 5,070 MeV, and 5,190 MeV, respectively. The average alpha particle energies for Cf-250 and Cf-252 are 6,024 MeV and 6,111 MeV. An example calculation of risk coefficient for inhalation of Cm-248 is shown below.

$$
\begin{aligned}
SF\left({}^{248}Cm\right) &= \frac{DF\left({}^{248}Cm\right)}{DF\left({}^{246}Cm\right)} SF\left({}^{246}Cm\right) \\
&= \frac{0.555 \text{ mrem/pCi}}{0.155 \text{ mrem/pCi}}\left(2.77x10^{-8} \text{ risk/pCi inhaled}\right) \\
&= 9.89x10^{-8} \text{ risk/pCi}
\end{aligned}
$$

Table A29. Cancer Morbidity Risk Coefficients for Internal Exposures, risk/pCi.

Nuclide	GI Absorption Fraction (f1)	Ingestion Risk Coefficients (risk/pCi ingested)			ICRP Lung Class	Inhalation (risk/pCi inhaled)
		Water	Food	Soil		
H-3	1	1.12E-13	1.44E-13	2.20E-13	M	1.99E-13
Be-10	0.005	7.03E-12	1.02E-11	2.02E-11	S	9.40E-11
C-14	1	1.55E-12	2.00E-12	2.79E-12	M	7.07E-12
Na-22	1	9.62E-12	1.26E-11	1.97E-11	F	3.89E-12
Al-26	0.01	1.73E-11	2.49E-11	4.70E-11	M	6.92E-11
Si-32+D	0.01	1.24E-11	1.73E-11	3.19E-11	S	3.05E-10
Cl-36	1	3.30E-12	4.44E-12	7.66E-12	M	2.50E-11
K-40	1	2.47E-11	3.43E-11	6.18E-11	F	1.03E-11
Ca-41	0.3	3.53E-13	4.37E-13	5.74E-13	M	2.09E-13
Ti-44+D	0.01	2.72E-11	3.87E-11	7.15E-11	F	2.02E-10
V-49	0.01	1.22E-13	1.79E-13	3.53E-13	M	1.47E-13
Mn-54	0.1	2.28E-12	3.11E-12	5.14E-12	M	5.88E-12
Fe-55	0.1	8.62E-13	1.16E-12	2.09E-12	M	7.99E-13
Fe-60+D	0.1	1.80E-10	2.39E-10	3.53E-10	M	1.84E-10
Co-60	0.1	1.57E-11	2.23E-11	4.03E-11	M	3.58E-11
Ni-59	0.05	2.74E-13	3.89E-13	7.33E-13	M	4.66E-13
Ni-63	0.05	6.70E-13	9.51E-13	1.79E-12	M	1.64E-12
Se-79	0.8	7.29E-12	9.69E-12	1.60E-11	F	3.33E-12
Rb-87	1	5.22E-12	7.07E-12	1.25E-11	F	2.14E-12

Table A29. Cancer Morbidity Risk Coefficients for Internal Exposures, risk/pCi.

Nuclide	GI Absorption Fraction (f1)	Ingestion Risk Coefficients (risk/pCi ingested)			ICRP Lung Class	Inhalation (risk/pCi inhaled)
		Water	Food	Soil		
Sr-90+D	0.3	7.40E-11	9.53E-11	1.44E-10	M	1.13E-10
Zr-93	0.01	1.11E-12	1.44E-12	2.12E-12	M	7.29E-12
Nb-91	0.01	8.03E-13	1.17E-12	2.31E-12	M	1.90E-12
Nb-93m	0.01	8.03E-13	1.17E-12	2.31E-12	M	1.90E-12
Nb-94	0.01	7.77E-12	1.11E-11	2.05E-11	M	3.77E-11
Mo-93	1	3.35E-12	4.18E-12	5.29E-12	M	1.27E-12
Tc-99	0.5	2.75E-12	4.00E-12	7.66E-12	M	1.41E-11
Ru-106+D	0.05	4.22E-11	6.11E-11	1.19E-10	M	1.02E-10
Pd-107	0.005	2.50E-13	3.67E-13	7.25E-13	S	1.69E-12
Ag-108m+D	0.05	8.14E-12	1.12E-11	1.92E-11	M	2.67E-11
Cd-109	0.05	5.00E-12	6.70E-12	1.14E-11	F	1.48E-11
Cd-113m	0.05	2.87E-11	3.64E-11	5.11E-11	F	1.30E-10
In-115	0.02	3.38E-11	4.33E-11	5.85E-11	F	4.03E-10
Sn-121m+D	0.02	3.50E-12	5.12E-12	1.00E-11	M	1.62E-11
Sn-126+D	0.02	2.72E-11	3.92E-11	7.50E-11	M	1.01E-10
Sb-125	0.1	4.37E-12	6.14E-12	1.12E-11	M	1.66E-11
Te-125m	0.3	3.33E-12	4.70E-12	8.92E-12	M	1.17E-11
I-129	1	1.48E-10	1.93E-10	2.71E-10	F	6.07E-11
Cs-134	1	4.22E-11	5.14E-11	5.81E-11	F	1.65E-11
Cs-135	1	4.74E-12	5.88E-12	7.18E-12	F	1.86E-12
Cs-137+D	1	3.04E-11	3.74E-11	4.33E-11	F	1.19E-11
Ba-133	0.2	6.81E-12	9.44E-12	1.39E-11	M	1.16E-11
Pm-147	0.0005	1.69E-12	2.48E-12	4.88E-12	S	1.61E-11
Sm-147	0.0005	3.74E-11	4.77E-11	7.59E-11	M	6.88E-09
Sm-151	0.0005	5.55E-13	8.07E-13	1.59E-12	M	4.88E-12
Eu-150	0.0005	4.33E-12	6.07E-12	1.08E-11	M	1.12E-10
Eu-152	0.0005	6.07E-12	8.70E-12	1.62E-11	M	9.10E-11
Eu-154	0.0005	1.03E-11	1.49E-11	2.85E-11	M	1.15E-10
Eu-155	0.0005	1.90E-12	2.77E-12	5.40E-12	M	1.48E-11
Gd-152	0.0005	2.97E-11	3.85E-11	6.29E-11	F	9.10E-09
Ho-166m	0.0005	8.03E-12	1.14E-11	2.10E-11	M	3.09E-10
Re-187	0.8	1.79E-14	2.56E-14	4.81E-14	M	2.51E-14
Tl-204	1	5.85E-12	8.25E-12	1.54E-11	F	2.45E-12
Pb-205	0.2	6.33E-13	8.25E-13	1.26E-12	M	6.44E-13
Pb-210+D	0.2	8.90E-10	1.19E-09	1.87E-09	M	3.09E-09
Bi-207	0.05	5.66E-12	8.14E-12	1.49E-11	M	2.10E-11
Po-209	(l)	4.70E-10	2.81E-09	9.93E-10	M	1.35E-08
Po-210	(l)	3.77E-10	2.25E-09	7.96E-10	M	1.08E-08
Ra-226+D	0.2	3.86E-10	5.15E-10	7.30E-10	M	1.16E-08
Ra-228+D	0.2	1.04E-09	1.43E-09	2.29E-09	M	5.21E-09
Ac-227+D	0.0005	4.87E-10	6.54E-10	1.16E-09	M	1.40E-07
Th-228+D	0.0005	3.01E-10	4.24E-10	8.12E-10	S	1.43E-07
Th-229+D	0.0005	5.28E-10	7.16E-10	1.29E-09	S	2.21E-07

Table A29. Cancer Morbidity Risk Coefficients for Internal Exposures, risk/pCi.

Nuclide	GI Absorption Fraction (f1)	Ingestion Risk Coefficients (risk/pCi ingested)			ICRP Lung Class	Inhalation (risk/pCi inhaled)
		Water	Food	Soil		
Th-230	0.0005	9.10E-11	1.19E-10	2.02E-10	S	2.85E-08
Th-232	0.0005	1.01E-10	1.33E-10	2.31E-10	S	4.33E-08
Pa-231	0.0005	1.73E-10	2.26E-10	3.74E-10	M	4.07E-08
U-232	0.02	2.92E-10	3.85E-10	5.74E-10	M	1.95E-08
U-233	0.02	7.18E-11	9.69E-11	1.60E-10	M	1.16E-08
U-234	0.02	7.07E-11	9.55E-11	1.58E-10	M	1.14E-08
U-235+D	0.02	7.18E-11	9.76E-11	1.63E-10	M	1.01E-08
U-236	0.02	6.70E-11	9.03E-11	1.49E-10	M	1.05E-08
U-238+D	0.02	8.71E-11	1.21E-10	2.10E-10	M	9.35E-09
Np-237+D	0.0005	6.74E-11	9.10E-11	1.62E-10	M	1.77E-08
Pu-236	0.0005	7.47E-11	9.92E-11	1.74E-10	M	2.28E-08
Pu-238	0.0005	1.31E-10	1.69E-10	2.72E-10	M	3.36E-08
Pu-239	0.0005	1.35E-10	1.74E-10	2.76E-10	M	3.33E-08
Pu-240	0.0005	1.35E-10	1.74E-10	2.77E-10	M	3.33E-08
Pu-241+D	0.0005	1.76E-12	2.28E-12	3.29E-12	M	3.34E-10
Pu-242	0.0005	1.28E-10	1.65E-10	2.63E-10	M	3.13E-08
Pu-244+D	0.0005	1.44E-10	1.90E-10	3.14E-10	M	2.93E-08
Am-241	0.0005	1.04E-10	1.34E-10	2.17E-10	M	2.81E-08
Am-242m+D	0.0005	7.25E-11	9.03E-11	1.34E-10	M	1.57E-08
Am-243+D	0.0005	1.08E-10	1.42E-10	2.32E-10	M	2.70E-08
Cm-242	0.0005	3.85E-11	5.48E-11	1.05E-10	M	1.51E-08
Cm-243	0.0005	9.47E-11	1.23E-10	2.05E-10	M	2.69E-08
Cm-244	0.0005	8.36E-11	1.08E-10	1.81E-10	M	2.53E-08
Cm-245	0.0005	1.04E-10	1.35E-10	2.18E-10	M	2.77E-08
Cm-246	0.0005	1.02E-10	1.31E-10	2.12E-10	M	2.77E-08
Cm-247+D	0.0005	1.00E-10	1.31E-10	2.12E-10	M	2.50E-08
Cm-248	0.0005	3.74E-10	4.80E-10	7.77E-10	M	9.89E-08
Cm-250+D	0.0005	2.14E-09	2.75E-09	4.45E-09	M	5.54E-07
Bk-247	0.0005	1.24E-10	1.60E-10	2.49E-10	M	3.26E-08
Cf-248	0.0005	4.44E-11	6.22E-11	1.18E-10	M	1.81E-08
Cf-249	0.0005	1.27E-10	1.63E-10	2.54E-10	M	3.40E-08
Cf-250	0.0005	8.62E-11	1.12E-10	1.85E-10	M	2.66E-08
Cf-251	0.0005	1.32E-10	1.70E-10	2.67E-10	M	3.40E-08
Cf-252	0.0005	4.85E-11	6.30E-11	1.04E-10	M	1.56E-08

Notes:

- The risk coefficients are cancer morbidity values from Federal Guidance Report Number 13 (EPA-402-R-99-001). Values for five nuclides were obtained using proportions between the ICRP 72 internal dose factors shown in Table A21. In particular, Nb-91 values come from Nb-93m, Po-209 comes from Po-210, Cm-248 comes from Cm-246, Cm-250 comes from Cm-246, and Cf-252 comes from Cf-250.
- GI absorption fractions (i.e., f1 values), and lung types are the same as used in Table A21.
- For I-129, the ingestion of milk has a risk coefficient of 3.22E-10 per pCi ingested.
- Short-lived radioactive progeny included in the "+D" nuclides are in secular equilibrium with their parent nuclide.

Table A30. Risk Coefficients for External Exposure, risk/y per pCi/g.

Nuclide	Risk Coefficient	Nuclide	Risk Coefficient	Nuclide	Risk Coefficient
H-3	0.00E+00	Sn-121m+D	9.86E-10	Pa-231	1.39E-07
Be-10	7.43E-10	Sn-126+D	8.83E-06	U-232	5.98E-10
C-14	7.83E-12	Sb-125	1.81E-06	U-233	9.82E-10
Na-22	1.03E-05	Te-125m	6.95E-09	U-234	2.52E-10
Al-26	1.33E-05	I-129	6.10E-09	U-235+D	5.43E-07
Si-32+D	9.43E-09	Cs-134	7.10E-06	U-236	1.25E-10
Cl-36	1.74E-09	Cs-135	2.36E-11	U-238+D	9.64E-08
K-40	7.97E-07	Cs-137+D	2.54E-06	Np-237+D	7.97E-07
Ca-41	0.00E+00	Ba-133	1.44E-06	Pu-236	1.19E-10
Ti-44+D	1.02E-05	Pm-147	3.21E-11	Pu-238	7.22E-11
V-49	0.00E+00	Sm-147	0.00E+00	Pu-239	2.00E-10
Mn-54	3.89E-06	Sm-151	3.60E-13	Pu-240	6.98E-11
Fe-55	0.00E+00	Eu-150	6.49E-06	Pu-241+D	1.31E-11
Fe-60+D	1.86E-08	Eu-152	5.30E-06	Pu-242	6.25E-11
Co-60	1.24E-05	Eu-154	5.83E-06	Pu-244+D	1.52E-06
Ni-59	0.00E+00	Eu-155	1.24E-07	Am-241	2.76E-08
Ni-63	0.00E+00	Gd-152	0.00E+00	Am-242m+D	4.75E-08
Se-79	1.10E-11	Ho-166m	7.69E-06	Am-243+D	6.36E-07
Rb-87	9.11E-11	Re-187	0.00E+00	Cm-242	7.73E-11
Sr-90+D	1.96E-08	Tl-204	2.76E-09	Cm-243	4.19E-07
Zr-93	0.00E+00	Pb-205	3.50E-12	Cm-244	4.85E-11
Nb-91	5.07E-09	Pb-210+D	4.17E-09	Cm-245	2.38E-07
Nb-93m	3.83E-11	Bi-207	7.08E-06	Cm-246	4.57E-11
Nb-94	7.29E-06	Po-209	1.32E-08	Cm-247+D	1.37E-06
Mo-93	2.17E-10	Po-210	3.95E-11	Cm-248	3.42E-11
Tc-99	8.14E-11	Ra-226+D	8.49E-06	Cm-250+D	1.43E-06
Ru-106+D	9.66E-07	Ra-228+D	4.53E-06	Bk-247	3.09E-07
Pd-107	0.00E+00	Ac-227+D	1.47E-06	Cf-248	4.73E-11
Ag-108m+D	7.19E-06	Th-228+D	7.81E-06	Cf-249	1.37E-06
Cd-109	8.73E-09	Th-229+D	1.16E-06	Cf-250	4.48E-11
Cd-113m	4.45E-10	Th-230	8.19E-10	Cf-251	3.76E-07
In-115	2.70E-10	Th-232	3.42E-10	Cf-252	8.66E-11

Notes:

- The risk coefficients for external exposure are cancer morbidity values from Federal Guidance Report Number 13 (EPA-402-R-99-001). Values for Nb-91 and Po-209 were estimated from the dose rate factors in Table A23 as described in the text.
- Short-lived radioactive progeny included in the "+D" nuclides are in secular equilibrium with their parent nuclide.

A3.8 Slope Factors and Reference Doses for Chemicals

For chemicals, the risk to the exposed individual of developing some type of cancer as well as non-cancer effects are of interest in human health risk assessments. The cancer risk is based on cancer induction slope factors, while the hazard from non-cancer effects is based on reference doses. Values for reference doses and slope factors adopted by the EPA are listed in the IRIS database. A somewhat larger version of the IRIS database is available from the Risk Assessment Information System (RAIS). The Oak Ridge National Laboratory (ORNL) maintains this toxicological data listing for human health risk assessments. The data may be obtained from the World Wide Web using the location http://risk.lsd.ornl.gov.

The reference dose and cancer slope factors are expressed in terms of the average daily dose. This dose is normalized to the mass of the recipient, and has units of mg/kg per day. Reference doses and cancer induction slope factors for the chemicals of interest are listed in Table A31. These values were found in IRIS and the RAIS databases during June, 2003. There are only two kinds at present, ingestion and inhalation. Reference doses and cancer induction slope factors for dermal absorption use the ingestion values. The reference doses and cancer induction slope factors for children are assumed to be the same as those for adults.

Table A31. Reference Doses and Cancer Induction Slope Factors for Chemicals.

		Reference Dose (mg/kg-day)		Cancer Slope Factor $(mg/kg\text{-}day)^{-1}$	
CASRN	Chemical Name	Ingestion	Inhalation	Ingestion	Inhalation
50-32-8	Benzo[a]pyrene	na	na	7.30E+00 e	na
53-70-3	Dibenz[a,h]anthracene	na	na	7.30E+00 r	3.08E+00 r
56-23-5	Carbon tetrachloride	7.00E-04 e	na	1.30E-01 e	5.25E-02 e
57-12-5	Cyanide, free	2.00E-02 e	na	na	na
57-14-7	1,1-Dimethylhydrazine	na	na	3.00E+00 r	1.72E+01 r
57-55-6	Propylene glycol (1,2-Propanediol)	2.00E+01 h	na	na	na
58-89-9	gamma-Benzene hexachloride (gamma-Lindane)	3.00E-04 e	na	1.30E+00 h	na
60-34-4	Methylhydrazine	na	na	3.00E+00 r	1.72E+01 r
60-57-1	Dieldrin	5.00E-05 e	na	1.60E+01 e	1.61E+01 e
62-75-9	N-Nitrosodimethylamine	na	na	5.10E+01 e	4.90E+01 e
64-18-6	Formic acid	2.00E+00 h	na	na	na
67-56-1	Methanol (Methyl alcohol)	5.00E-01 e	na	na	na
67-64-1	Acetone (2-Propanone)	1.00E-01 e	na	na	na
67-66-3	Chloroform	1.00E-02 e	na	1.00E-03 e	8.05E-02 e
71-36-3	n-Butyl alcohol (n-Butanol)	1.00E-01 e	na	na	na
71-43-2	Benzene	4.00E-03 e	8.57E-03 e	5.50E-02 e	2.73E-02 e
71-55-6	1,1,1-Trichloroethane (Methyl chloroform)	2.00E-01 r	6.29E-01 r	na	na
72-20-8	Endrin	3.00E-04 e	na	na	na
74-83-9	Bromomethane	1.40E-03 e	1.43E-03 e	na	na
74-87-3	Methyl chloride (Chloromethane)	na	2.57E-02 e	na	na
75-00-3	Ethyl Chloride	na	2.86E+00 e	na	na
75-01-4	Vinyl chloride (Chloroethene)	3.00E-03 e	2.86E-02 e	1.40E+00 e	3.08E-02 e
75-05-8	Acetonitrile	na	1.71E-02 e	na	na
75-07-0	Acetaldehyde	na	2.57E-03 e	na	7.70E-03 e

Table A31. Reference Doses and Cancer Induction Slope Factors for Chemicals.

CASRN	Chemical Name	Reference Dose (mg/kg-day)		Cancer Slope Factor $(mg/kg\text{-}day)^{-1}$	
		Ingestion	Inhalation	Ingestion	Inhalation
75-09-2	Dichloromethane (Methylene chloride)	6.00E-02 e	8.57E-01 h	7.50E-03 e	1.65E-03 e
75-15-0	Carbon disulfide	1.00E-01 e	2.00E-01 e	na	na
75-21-8	Ethylene Oxide (Oxirane)	na	na	1.02E+00 h	3.50E-01 h
75-34-3	1,1-Dichloroethane (Ethylidene chloride)	1.00E-01 h	1.43E-01 h	na	na
75-35-4	1,1-Dichloroethylene	5.00E-02 e	5.71E-02 e	na	na
75-45-6	Chlorodifluoromethane	na	1.43E+01 e	na	na
75-68-3	Chloro-1,1-difluoroethane, 1-	na	1.43E+01 e	na	na
75-69-4	Trichlorofluoromethane	3.00E-01 e	2.00E-01 h	na	na
75-71-8	Dichlorodifluoromethane	2.00E-01 e	5.71E-02 h	na	na
76-13-1	1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113)	3.00E+01 e	8.57E+00 h	na	na
76-44-8	Heptachlor	5.00E-04 e	na	4.50E+00 e	4.55E+00 e
78-87-5	1,2-Dichloropropane	na	1.14E-03 e	na	na
78-93-3	Methyl ethyl ketone (2-Butanone)	6.00E-01 e	2.86E-01 e	na	na
79-00-5	1,1,2-Trichloroethane	4.00E-03 e	na	5.70E-02 e	5.60E-02 e
79-01-6	Trichloroethylene	6.00E-03 r	na	1.10E-02 r	5.95E-03 r
79-10-7	2-Propenoic acid (Acrylic acid)	5.00E-01 e	2.86E-04 e	na	na
79-34-5	1,1,2,2-Tetrachloroethane (Acetylene tetrachloride)	na	na	2.00E-01 e	2.03E-01 e
82-68-8	Pentachloronitrobenzene (PCNB)	3.00E-03 e	na	2.60E-01 h	na
83-32-9	Acenaphthene	6.00E-02 e	na	na	na
84-66-2	Diethyl phthalate	8.00E-01 e	na	na	na
84-74-2	Dibutyl phthalate	1.00E-01 e	na	na	na
85-68-7	Butyl benzyl phthalate	2.00E-01 e	na	na	na
87-68-3	Hexachlorobutadiene	2.00E-04 h	na	7.80E-02 e	7.70E-02 e
87-86-5	Pentachlorophenol	3.00E-02 e	na	1.20E-01 e	na
88-06-2	2,4,6-Trichlorophenol	na	na	1.10E-02 e	1.09E-02 e
88-85-7	2-sec-Butyl-4,6-dinitrophenol (Dinoseb)	1.00E-03 e	na	na	na
91-20-3	Naphthalene	2.00E-02 e	8.57E-04 e	na	na
92-52-4	1,1'-Biphenyl	5.00E-02 e	na	na	na
95-50-1	1,2-Dichlorobenzene (ortho-)	9.00E-02 e	na	na	na
95-63-6	1,2,4-Trimethylbenzene	5.00E-02 r	1.71E-03 r	na	na
98-86-2	Acetophenone	1.00E-01 e	na	na	na
98-95-3	Nitrobenzene	5.00E-04 e	5.71E-04 h	na	na
100-25-4	1,4-Dinitrobenzene (para-)	4.00E-04 h	na	na	na
100-41-4	Ethyl benzene	1.00E-01 e	2.86E-01 e	na	na
100-42-5	Styrene	2.00E-01 e	2.86E-01 e	na	na
100-51-6	Benzyl alchohol	3.00E-01 h	na	na	na
106-46-7	1,4-Dichlorobenzene (para-)	na	2.29E-01 e	2.40E-02 h	na
106-93-4	1,2-Dibromoethane (Ethylene dibromide)	na	5.71E-05 h	8.50E+01 e	7.70E-01 e
106-99-0	1,3-Butadiene	na	5.71E-04 e	na	1.05E-01 e
107-02-8	Acrolein	5.00E-04 e	5.71E-06 e	na	na
107-05-1	3-Chloropropene (Allyl chloride)	5.00E-02 h	2.86E-04 e	na	na

Table A31. Reference Doses and Cancer Induction Slope Factors for Chemicals.

CASRN	Chemical Name	Reference Dose (mg/kg-day)		Cancer Slope Factor $(mg/kg\text{-}day)^{-1}$	
		Ingestion	Inhalation	Ingestion	Inhalation
107-06-2	1,2-Dichloroethane (Ethylene chloride)	na	na	9.10E-02 e	9.10E-02 e
107-13-1	Acrylonitrile	1.00E-03 h	5.71E-04 e	5.40E-01 e	2.38E-01 e
108-10-1	Methyl isobutyl ketone (4-Methyl-2-pentanone)	na	8.57E-01 e	na	na
108-67-8	1,3,5-Trimethylbenzene	5.00E-02 r	1.71E-03 r	na	na
108-87-2	Methyl cyclohexane	na	8.57E-01 r	na	na
108-88-3	Toluene (Methyl benzene)	2.00E-01 e	1.14E-01 e	na	na
108-90-7	Chlorobenzene	2.00E-02 e	5.71E-03 h	na	na
108-94-1	Cyclohexanone	5.00E+00 e	na	na	na
108-95-2	Phenol (Carbolic acid)	3.00E-01 e	na	na	na
110-00-9	Furan (Oxacyclopentadiene)	1.00E-03 e	na	na	na
110-54-3	n-Hexane	6.00E-02 h	5.71E-02 e	na	na
110-86-1	Pyridine	1.00E-03 e	na	na	na
111-76-2	2-Butoxyethanol (Ethylene Glycol Monobutyl Ether)	5.00E-01 e	3.71E+00 e	na	na
111-90-0	2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether)	2.00E+00 h	na	na	na
117-81-7	Di (2-ethylhexyl) phthalate (DEHP)	2.00E-02 e	na	1.40E-02 e	na
117-84-0	Di-n-octylphthalate	2.00E-02 h	na	na	na
118-74-1	Hexachlorobenzene	8.00E-04 e	na	1.60E+00 e	1.61E+00 e
120-82-1	1,2,4-Trichlorobenzene	1.00E-02 e	5.71E-02 h	na	na
121-44-8	Triethylamine	na	2.00E-03 e	na	na
122-39-4	Diphenylamine	2.50E-02 e	na	na	na
123-91-1	1,4-Dioxane (Diethylene oxide)	na	na	1.10E-02 e	na
126-73-8	Tributyl Phosphate	2.00E-01 r	na	5.40E-03 r	na
126-98-7	2-Methyl-2-propenenitrile (Methacrylonitrile)	1.00E-04 e	2.00E-04 h	na	na
127-18-4	1,1,2,2-Tetrachloroethylene	1.00E-02 e	1.71E-01 r	5.20E-02 r	2.03E-03 r
141-78-6	Ethyl acetate (Acetic acid, ethyl ester)	9.00E-01 e	na	na	na
156-59-2	cis-1,2-Dichloroethylene	1.00E-02 h	na	na	na
206-44-0	Fluoranthene (1,2-Benzacenaphthene)	4.00E-02 e	na	na	na
309-00-2	Aldrin	3.00E-05 e	na	1.70E+01 e	1.72E+01 e
319-84-6	alpha-Benzene hexachloride (alpha-Lindane)	na	na	6.30E+00 e	6.30E+00 e
319-85-7	beta-Benzene hexachloride (beta-Lindane)	na	na	1.80E+00 e	1.86E+00 e
621-64-7	N-Nitrosodi-N-propylamine	na	na	7.00E+00 e	na
1314-62-1	Vanadium pentoxide	9.00E-03 e	na	na	na
1330-20-7	Xylenes (mixtures)	2.00E-01 e	2.86E-02 e	na	na
1336-36-3	Polychlorinated Biphenyls (high risk)	na	na	2.00E+00 e	na
1336-36-3	Polychlorinated Biphenyls (low risk)	na	na	4.00E-01 e	na
1336-36-3	Polychlorinated Biphenyls (lowest risk)	na	na	7.00E-02 e	na
6533-73-9	Thallium carbonate	8.00E-05 e	na	na	na
7429-90-5	Aluminum	1.00E+00 r	1.43E-03 r	na	na
7439-96-5	Manganese	1.40E-01 e	1.43E-05 e	na	na
7439-98-7	Molybdenum	5.00E-03 e	na	na	na

Table A31. Reference Doses and Cancer Induction Slope Factors for Chemicals.

CASRN	Chemical Name	Reference Dose (mg/kg-day)		Cancer Slope Factor $(mg/kg\text{-}day)^{-1}$	
		Ingestion	Inhalation	Ingestion	Inhalation
7440-02-0	Nickel (soluble salts)	2.00E-02 e	na	na	na
7440-22-4	Silver	5.00E-03 e	na	na	na
7440-24-6	Strontium, Stable	6.00E-01 e	na	na	na
7440-31-5	Tin	6.00E-01 h	na	na	na
7440-36-0	Antimony	4.00E-04 e	na	na	na
7440-38-2	Arsenic (inorganic)	3.00E-04 e	na	1.50E+00 e	1.51E+01 e
7440-39-3	Barium	7.00E-02 e	1.43E-04 h	na	na
7440-41-7	Beryllium and compounds	2.00E-03 e	5.71E-06 e	na	8.40E+00 e
7440-42-8	Boron and borates only	9.00E-02 e	5.71E-03 h	na	na
7440-43-9	Cadmium	5.00E-04 e	na	na	6.30E+00 e
7440-48-4	Cobalt	2.00E-02 r	5.71E-06 r	na	9.80E+00 r
7440-66-6	Zinc and compounds	3.00E-01 e	na	na	na
7487-94-7	Mercuric chloride	3.00E-04 e	na	na	na
7664-41-7	Ammonia	na	2.86E-02 e	na	na
7723-14-0	Phosphorus, white	2.00E-05 e	na	na	na
7782-41-4	Fluorine (soluble fluoride)	6.00E-02 e	na	na	na
7782-49-2	Selenium and compounds	5.00E-03 e	na	na	na
8001-35-2	Toxaphene	na	na	1.10E+00 e	1.12E+00 e
14797-55-8	Nitrate	1.60E+00 e	na	na	na
14797-65-0	Nitrite	1.00E-01 e	na	na	na
16065-83-1	Chromium (III) (insoluble salts)	1.50E+00 e	na	na	na
18540-29-9	Chromium (VI) (soluble salts)	3.00E-03 e	2.29E-06 e	na	4.20E+01 e
none	Uranium (soluble salts)	6.00E-04 e	na	na	na

Notes:
- CASRN = Chemical Abstract Service Reference Number
- "e" means the number is from IRIS as of June, 2003
- "r" means the number is from RAIS as of June, 2003
- "h" means the number in RAIS is from HEAST
- **Slope factors** give an upper bound on the probability that some type of cancer develops as a result of a lifetime exposed to a given chemical. The risk is multiplied by the lifetime average daily chemical dose to give the lifetime risk. Two special cases are noted below.
- The slope factors for vinyl chloride (CAS 75-01-4) apply to the general population. When applying these to occupationally exposed individuals (industrial exposure scenario), the values are reduced by a factor of 2.
- The slope factors for PCBs (CAS 1336-36-3) are reduced for population (collective) exposures. The slope factors used for high, low and lowest risk PCBs are 1.0, 0.3, and 0.04 per mg/kg per day.
- **Reference dose** is an estimate of a daily dose to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. Special cases are noted below.
- The RfD for manganese in drinking water is 1/3 the dietary RfD shown on the table.
- The RfD for dietary cadmium is twice the drinking water RfD shown on the table.
- The RfD for airborne particulate containing chromium (VI) is 2.86E-05 mg/kg per day.

Several chemicals have a reference dose or slope factor given for ingestion, but none for inhalation, or vice-versa. Rather than omit this chemical, the calculations were carried out with only the given route of exposure (inhalation or ingestion/dermal). The missing route was ignored. Since this omission can grossly underestimate the risk from a chemical, the importance of the missing value was examined in Appendix C. Using simple methods for estimating the missing reference dose or slope factor, and looking for hazard quotients and cancer risks that double, leads to a list of chemicals whose missing parameter may be important. This list is shown in Table C2.

A4.0 ANIMAL PARAMETERS

The animal parameters discussed here are those pertaining to the eventual concentration of a contaminant in animal products consumed as food, such as fish, milk, meat, poultry, and eggs. The model used to represent various animals assumes contaminants are taken in by inhalation, ingestion, and dermal absorption at a rate that changes slowly during the year. The concentration in the animal reaches a steady-state maximum related to the concentration in its environment. This is a type of equilibrium in which the intake rate of a contaminant is the same as the loss rate, hence, the concentration in the animal product is constant.

Note that the radiation doses received by the animals are assumed to be low enough to not affect their health or metabolism. In equilibrium, the contaminant concentration in the animal product is proportional to the ingestion rate of contamination by the animal. The constants of proportionality are called bioaccumulation factors, or equilibrium transfer factors.

Not all animals have transfer factors developed for them. It is assumed that other aquatic animals such as bottom-dwelling fish, crustaceans and mollusks are consumed in minimal amounts. If a group of people is identified who consume significant quantities of these creatures then efforts will be made to quantify the transfer factors that would apply to them. Other land animals such as pigs or goats or deer are assumed to have transfer factors that differ very little from cattle.

The contaminant concentration in cattle and poultry depends on the rate at which the contaminant is consumed. The cattle and poultry diets are discussed in the next section. The equilibrium transfer factors for these animals are discussed afterward.

A4.1 General Animal Parameters and Pasture Area

The daily intake rates assumed for cattle and poultry are listed in Table A32. These are from NUREG/CR-5512, Section 6.5.1. No distinction is made between the diets of poultry raised for food and egg-laying hens. For comparison with prior Hanford Site performance assessments, the default intake rates used by the GENII program (PNNL-6584) are also shown in Table A32. The water intake rates are the same for both. Note that the GENII program does not distinguish between the two types of stored feed (i.e. hay or grain), nor does it allow the animals to ingest soil directly.

To calculate the contaminant concentrations in the animal foods, it is necessary to introduce a "dry-to-wet ratio". The "dry-to-wet ratio" is a unitless quantity measured as the ratio of the dry weight of the item to its wet weight. The "dry-to-wet ratio" for stored hay applies at the time of harvest. (In practice the hay is dried before being fed to cattle. Thus the "dry-to-wet ratio" for sun-cured hay is reported as approximately 0.9, similar to stored grain.)

The intake rates found in NUREG/CR-5512 will be used in the current performance assessment, as they were in the 2001 ILAW PA. The principal reason for this change from prior Hanford performance assessments is the extra detail provided for the diet. Previous performance assessments relied on the GENII software Version 1.485, which is unable to accommodate this detail. The tank waste PA for the low-level waste glass form will utilize hand calculations that incorporate the added detail.

Table A32. Animal Feed, Water, and Soil Intake Rates.

Values from NUREG/CR-5512 for use in the tank waste PA							
Type of Feed	**dry-to-wet ratio**	**Beef, kg/d**		**Milk, kg/d**		**Poultry, kg/d**	
		dry	**wet**	**dry**	**wet**	**dry**	**wet**
Fresh Forage	0.22	3	27	8	36	0.0275	0.13
Stored Hay	0.22	6	14	6	29	0	0
Stored Grain	0.91	3	3	2	2	0.0825	0.09
	Total Feed, kg/d:	12	44	16	67	0.110	0.22
	Soil Ingestion Rate:	0.6 kg/d		0.8 kg/d		0.011 kg/d	
	Drinking Water:	50 L/d		60 L/d		0.3 L/d	
Values from GENII Version 1.485 (PNNL-6584) used in previous Hanford Site PAs							
Type of Feed	**dry-to-wet ratio**	**Beef, kg/d**		**Milk, kg/d**		**Poultry, kg/d**	
		dry	**wet**	**dry**	**wet**	**dry**	**wet**
Fresh Forage	0.20	10	51	8	41	0	0
Stored Hay	0.18	3	17	2	14	0.022	0.12
Stored Grain	NA	NA	NA	NA	NA	NA	NA
	Total Feed, kg/d:	13	68	10	55	0.022	0.12
	Soil Ingestion Rate:	NA		NA		NA	
	Drinking Water:	50 L/d		60 L/d		0.3 L/d	
The wet weights for fresh forage and stored hay are at the time of harvest or grazing. The GENII software (Version 1.485) has one type of stored feed that uses the soil-to-plant concentration factors for grains. In addition, GENII does not consider ingestion of soil by grazing animals.							

The exposure of special groups living near waste sites or near locations where the ground water enters the Columbia River would probably include the consumption of some type of native game animals. These animals could acquire radioactivity from drinking and grazing near locations were ground water enters the river. The larger examples of these, such as deer, would graze over a large area. Thus only a small portion of the deer’s plant intakes would be contaminated. Similarly, the smaller animals might derive all of their nourishment from a contaminated area. However, such animals would have to be harvested from many locations over the course of a year. The average concentration from all such animals would be much lower due to the large forage area needed for hunting and gathering. For the cases where the ground water is the main source of contamination, it will be assumed that the game animals are contaminated at such a low level compared with the domesticated animals that the dose from game animals can be ignored. For the cases where the Columbia River is the main source of contaminated water, the animals will be assumed to obtain all of their drinking water from the river, but their vegetation intakes will be assumed uncontaminated. The transfer factors for beef will be used to represent transfer to the edible portion of the deer. The daily water intake for the deer is assumed to be 25% that of the milk cow. Waterfowl are similarly represented using the poultry data, except there is no difference in the daily water intake.

It should be noted that animals killed by native hunters would be more efficiently scavenged than common farm animals. Some of the internal organs would be eaten. The animal skins could be used for clothing, and larger bones could be used as tools or ceremonial items. The more extensive use of animal parts could increase the exposed person's radiation dose. Nevertheless, it will be assumed that this dose is small compared with that from farm animals.

The land area needed to support a cow can be calculated from the consumption rates given in Table A32. A search of the internet for “pasture size” or “animal unit month” uncovers numerous reports dealing with estimating how much land is needed to support grazing cows. One common factor in the calculations is the fraction of the grass lost to trampling. The usual factor is 40%, which will be used here also. An additional consideration is the fraction of the standing biomass that the cow can eat. The usual factor is 50%, which will be used here also. Additional factors, such as the standing biomass and growing period are presented in Table A39 below. An irrigation period of 0.5 y means that there are 6 crops of grass (30 d each). The irrigation period (i.e., the grazing period) cancels out of the equation below.

$$A_{Grass} = \frac{M_{Grass}\ T_{Grow,Grass}}{Y_{Grass}\ F_{Eaten}\left(1 - F_{Trample}\right)} = \frac{(36\ \text{kg/d})(30\ \text{d})}{\left(1.5\ \text{kg/m}^2\right)(0.5)(1-0.4)} = 2{,}400\ \text{m}^2$$

where,

A_{Grass}	=	pasture grass area needed for the milk cow, 2,400 m^2
F_{Eaten}	=	fraction of standing biomass eaten by the cow while grazing, 0.5
$F_{Trample}$	=	fraction of the standing biomass trampled by the cow while grazing, 0.4
M_{Grass}	=	mass of grass eaten each day by the cow from Table A32, 36 kg (wet)/d
$T_{Grow,Grass}$	=	growing period for the grass from Table A39, 30 days
Y_{Grass}	=	standing biomasss for mature grass from Table A39, 1.5 kg/m^2

A similar equation is needed for the hay field. The hay grows during the irrigation period and is consumed by the cow during the remainder of the year, the no-irrigation period. An irrigation period of 0.5 y means there are 4 crops of hay (45 d each). Since the hay growing period is the same length as the hay consumption period, it cancels out of the equation below. The loss from trampling is not needed, but the fraction harvested is used. The harvested fraction is assumed to be the same as the fraction that the cow eats while grazing, 50%.

$$A_{Hay} = \frac{M_{Hay}\ T_{Grow,Hay}}{Y_{Hay}\ F_{Harvest}} = \frac{(29\ \text{kg/d})(45\ \text{d})}{\left(1.0\ \text{kg/m}^2\right)(0.5)} = 2{,}600\ \text{m}^2$$

where,

A_{Hay}	=	hay field area needed for the milk cow, 2,600 m^2
$F_{Harvest}$	=	fraction of standing biomass harvested for the cow, 0.5

M_{Hay} = mass of hay eaten each day by the cow from Table A32, 29 kg (wet)/d
$T_{Grow,Hay}$ = growing period for the grass from Table A39, 45 days
Y_{Hay} = standing biomasss for mature grass from Table A39, 1.5 kg/m^2

A4.2 Equilibrium Transfer Factors for Radionuclides

The equilibrium transfer factors for cattle and poultry relate the rate of intake of a radionuclide to the eventual steady-state concentration in meat or milk or eggs. These parameters are the ratio of the equilibrium concentration of a nuclide in the animal product to the daily intake by the animal. For beef, poultry and eggs the units are Ci/kg per Ci/d (equivalent to d/kg), while for milk the units are Ci/L(milk) per Ci/d (equivalent to d/L). Transfer factors for organs such as liver or brain are not available. Since some elements may be found in higher concentrations in these tissues, individuals who consume the organs would receive higher doses from the radioactive isotopes of the elements.

The concentration of waterborne contaminants in fish is assumed to be proportional to the concentration of the contaminant in the water environment of the fish. The constant of proportionality for fish is called a "bioaccumulation" factor. It is the average concentration of the contaminant in the edible portion of the fish divided by the concentration in the water. This parameter has units of L/kg. The transfer factors used in the present report for cows, chickens and fish are shown in Table A33. Bioaccumulation factors include the effects of contaminants in sediments, plant life, and other aquatic organisms contribute to contamination in the edible portions of the fish.

There are several sources for these transfer factors, as indicated by the letter beside each number in Table A33. The following hierarchy is used for selecting values. The first values are chosen from PNWD-2023. This report compiled Hanford-specific data developed for dose reconstruction of historical atmospheric releases from the Hanford Site. For elements that are not discussed in PNWD-2023, values from IAEA Technical Report 364 were chosen. The IAEA report is a compilation from many sources. For elements not discussed in the IAEA report, values from ORNL-5786 were used. For elements not discussed in these reports, values from NUREG/CR-5512 Volume 1 were chosen. For elements not discussed in those reports, values from NCRP-123 were used. A few elements still had no assigned values. In these cases values were assumed based on chemical similarities.

For cows and chickens it was necessary to assume values for berkelium (Bk). These were assumed to be the same as americium (Am). For the chicken it was necessary to assume values for boron (B), aluminum (Al), titanium (Ti), and vanadium (V). These were assumed to be the same as silicon (Si), gallium (Ga), scandium (Sc), and chromium (Cr), respectively.

For accumulation in cows and chickens, the PNWD-2023 report only supplied a value for transfer of iodine (I) to milk. The transfer factors for the other animal products are specified as a range and this range covers the values given in the IAEA report. For accumulation in fish, PNWD-2023 provides values for the elements sodium (Na), phosphorus (P), arsenic (As), and neptunium (Np). It is assumed that plutonium (Pu), americium (Am), and curium (Cm) share the same accumulation factor as Np.

Table A33. Transfer Factors for Radionuclides to Cows, Chickens, and Fish.

Element	Meat (day/kg)	Milk (day/L)	Poultry (day/kg)	Eggs (day/kg)	Fish (L/kg)	Atomic Number
H	na	na	na	na	1.0 b	1
Be	1.0E-03 c	9.0E-07 c	0.40 d	0.020 d	100 b	4
B	8.0E-04 c	1.5E-03 c	0.20 d	0.80 d	5.0 e	5
C	0.0489 f	0.0105 f	4.16 f	3.12 f	50,000 b	6
F	0.15 c	1.0E-03 c	0.010 d	2.0 d	10 d	9
Na	0.080 b	0.016 b	0.010 d	6.0 b	8.0 a	11
Al	1.5E-03 c	2.0E-04 c	0.30 d	0.80 d	500 e	13
Si	4.0E-05 c	2.0E-05 c	0.20 d	0.80 d	20 e	14
P	0.050 b	0.016 b	0.19 d	10 d	1,500 a	15
Cl	0.020 b	0.017 b	0.030 d	2.0 d	50 d	17
K	0.020 b	7.2E-03 b	0.40 d	1.0 b	1,000 d	19
Ca	2.0E-03 b	3.0E-03 b	0.040 b	0.40 b	40 d	20
Ti	0.030 c	0.010 c	4.0E-03 d	3.0E-03 d	1,000 e	22
V	2.5E-03 c	2.0E-05 c	0.20 d	0.80 d	200 e	23
Mn	5.0E-04 b	3.0E-05 b	0.050 b	0.060 b	400 b	25
Fe	0.020 b	3.0E-05 b	1.0 b	1.0 b	200 b	26
Co	0.010 b	3.0E-04 b	2.0 b	0.10 b	300 b	27
Ni	5.0E-03 b	0.016 b	1.0E-03 d	0.10 d	100 b	28
As	2.0E-03 c	6.0E-05 c	0.83 d	0.80 d	244 a	33
Se	0.015 c	4.0E-03 c	9.0 b	9.0 b	170 d	34
Rb	0.010 b	0.012 b	2.0 d	3.0 d	2,000 b	37
Sr	8.0E-03 b	2.8E-03 b	0.080 b	0.20 b	60 b	38
Y	1.0E-03 b	2.0E-05 c	0.010 b	2.0E-03 b	30 b	39
Zr	1.0E-06 b	5.5E-07 b	6.0E-05 b	2.0E-04 b	300 b	40
Nb	3.0E-07 b	4.1E-07 b	3.0E-04 b	1.0E-03 b	300 b	41
Mo	1.0E-03 b	1.7E-03 b	1.0 b	0.90 b	10 b	42
Tc	1.0E-04 b	1.4E-04 b	0.030 b	3.0 b	20 b	43
Ru	0.050 b	3.3E-06 b	0.24 b	5.0E-03 b	10 b	44
Pd	4.0E-03 c	0.010 c	3.0E-04 d	4.0E-03 d	10 d	46
Ag	3.0E-03 b	5.0E-05 b	2.0 b	0.50 d	5.0 b	47
Cd	4.0E-04 b	1.0E-03 c	0.80 b	0.10 b	200 d	48
In	8.0E-03 c	1.0E-04 c	0.30 d	0.80 d	100,000 d	49
Sn	0.080 c	1.0E-03 c	0.20 d	0.80 d	3,000 b	50
Sb	4.0E-05 b	2.5E-05 b	6.0E-03 d	0.070 d	100 b	51
Te	7.0E-03 b	4.5E-04 b	0.60 b	5.0 b	400 b	52
I	0.040 b	0.012 a	0.010 b	3.0 b	40 b	53
Cs	0.050 b	7.9E-03 b	2.0 b	0.40 b	2,000 b	55
Ba	2.0E-04 b	4.8E-04 b	9.0E-03 b	0.90 b	4.0 b	56
Pm	5.0E-03 c	2.0E-05 c	2.0E-03 b	0.020 b	30 b	61
Sm	5.0E-03 c	2.0E-05 c	4.0E-03 d	7.0E-03 d	25 d	62
Eu	5.0E-03 c	2.0E-05 c	4.0E-03 d	7.0E-03 d	50 b	63
Gd	3.5E-03 c	2.0E-05 c	4.0E-03 d	7.0E-03 d	25 d	64
Ho	4.5E-03 c	2.0E-05 c	4.0E-03 d	7.0E-03 d	25 d	67
Re	8.0E-03 c	1.5E-03 c	0.040 d	0.40 d	120 d	75
Hg	0.25 c	4.7E-04 b	0.030 b	0.20 d	1,000 b	80

Table A33. Transfer Factors for Radionuclides to Cows, Chickens, and Fish.

Element	Meat (day/kg)	Milk (day/L)	Poultry (day/kg)	Eggs (day/kg)	Fish (L/kg)	Atomic Number
Tl	0.040 c	2.0E-03 c	0.30 d	0.80 d	10,000 e	81
Pb	4.0E-04 b	2.5E-04 c	0.20 d	0.80 d	300 b	82
Bi	4.0E-04 c	5.0E-04 c	0.10 d	0.80 d	10 b	83
Po	5.0E-03 b	3.4E-04 b	0.90 d	7.0 d	50 b	84
Ra	9.0E-04 b	1.3E-03 b	0.030 d	2.0E-05 d	50 b	88
Ac	2.5E-05 c	2.0E-05 c	4.0E-03 d	2.0E-03 d	25 d	89
Th	6.0E-06 c	5.0E-06 c	4.0E-03 d	2.0E-03 d	100 b	90
Pa	1.0E-05 c	5.0E-06 c	4.0E-03 d	2.0E-03 d	10 b	91
U	3.0E-04 b	4.0E-04 b	1.0 b	1.0 b	10 b	92
Np	1.0E-03 b	5.0E-06 b	4.0E-03 d	2.0E-03 d	21 a	93
Pu	1.0E-05 b	1.1E-06 b	3.0E-03 b	5.0E-04 b	21 a	94
Am	4.0E-05 b	1.5E-06 b	6.0E-03 b	4.0E-03 b	21 a	95
Cm	3.5E-06 c	2.0E-05 c	4.0E-03 d	2.0E-03 d	21 a	96
Bk	4.0E-05 b	1.5E-06 b	6.0E-03 b	4.0E-03 b	25 e	97
Cf	5.0E-03 d	7.5E-07 d	4.0E-03 d	2.0E-03 d	25 d	98

Notes:

- All of the transfer factors are derived using the wet weights. Note that Egg values are for egg contents rather than the whole egg.
- Cow and chicken parameters were selected using the following hierarchy: (a) PNWD-2023, (b) IAEA #364, (c) ORNL-5786, and (d) NUREG/CR-5512. Bk is assumed the same as Am for all cow and chicken parameters. Cow and chicken transfer factors for carbon were computed from the equilibrium model described in the text (f). Values for hydrogen are not used in the calculations (na) because an equilibrium transfer model is used instead.
- For the Poultry and Egg (i.e. chicken), the values for Si are used for B, the values for Ga are used for Al, the values for Sc are used for Ti, and the values for Cr are used for V.
- Fish bioaccumulation factors were selected using the following hierarchy: (a) PNWD-2023, (b) IAEA #364, (c) ORNL-5786, (d) NUREG/CR-5512, and (e) NCRP #123.

Transfer factors for tritium (H-3) are not needed because the animal concentration is calculated using the equilibrium model described in the discussion of scenario dose factors. The transfer factors for C-14 are computed from an equilibrium model. The ratio of radioactive C-14 to the non-radioactive carbon in the animal's diet is assumed to be reproduced in the food product. The equilibrium transfer factor is then the fraction of carbon in the food product divided by the daily intake of carbon. The assumed element fractions are listed in Table A34 below. Values in this table were taken from NUREG/CR-5512. The formula to describe the calculation of C-14 transfer factors is shown below. Note that the carbon content of water is assumed insignificant.

$$B_{A,q,C-14} = \frac{F_{C,q}}{F_{C,s} M_{S,q} + \sum_{p} F_{C,p} M_{V,p,q}}$$

where,

$B_{A,q,C\text{-}14}$ = animal transfer factor for C-14 into animal product type q shown in Table A33, in day/kg

$F_{C,p}$ = mass fraction of carbon in fodder type p from Table A34

$F_{C,q}$ = mass fraction of carbon in animal product type q from Table A34

$F_{C,s}$ = mass fraction of carbon in garden soil from Table A34

$M_{S,q}$ = daily mass of soil ingested by animal type q in Table A32, in kg/d
$M_{V,p,q}$ = daily mass of animal fodder type p eaten by animal type q, in kg (wet)/d. These amounts are shown in Table A32.
p = index to the various types of animal fodder shown in Table A39
q = index to the four types of animal products, i.e., meat, milk, poultry, and eggs

The bioaccumulation factors shown in Table A33 are used to estimate total population dose from fish consumption to people living near the Columbia River. The edible portion of fish is the muscle normally cooked and consumed. The rest of the fish is assumed to be discarded. If there are individuals who eat or otherwise use other parts of the fish they could receive additional dose.

A subject requiring research is the equilibrium transfer factors for wild animals consuming native vegetation. These species may be "harvested" by humans for food. In addition, since standard uptake factors are for muscle tissue only, there would need to be organ-specific uptake factors for those organ meats that are consumed by special groups of people.

Table A34. Hydrogen and Carbon Fractions for Equilibrium Models.

Food Pathway Item	Hydrogen Fraction	Carbon Fraction
Garden Soil	0.0149	0.03
Leafy Vegetables	0.10	0.09
Other Vegetables	0.10	0.09
Fruit	0.10	0.09
Grain	0.068	0.40
Fresh Forage	0.10	0.09
Stored Hay	0.10	0.09
Stored Grain	0.068	0.40
Beef	0.10	0.24
Milk	0.11	0.07
Poultry	0.10	0.20
Eggs	0.11	0.15

Notes:
- All fractions listed above are based on the wet weight of the item. The effective water fraction is the hydrogen fraction times 8.94, which is the ratio of molecular weights for water and hydrogen.
- All fractions are taken from NUREG/CR-5512, except for the hydrogen fraction in garden soil, which is calculated as the product of the soil moisture content (20% by volume) and the density of water (1.0 kg/L) divided by the product of the soil density (1.5 kg/L) and 8.94.
- Hydrogen fractions include organically bound hydrogen as well as water.
- The carbon fraction for garden soil assumes the presence of organic matter not found in subsurface Hanford soil.

A4.3 Equilibrium Transfer Factors for Chemicals

As with radionuclides, the equilibrium transfer factors for cattle and poultry relate the rate of intake of a chemical to the eventual steady-state concentration in meat or milk or eggs. These parameters are the ratio of the equilibrium concentration of a chemical in the animal product to the daily intake by the animal. The units are g/kg per g/d (equivalent to d/kg). Transfer factors for chemicals are scarce. The need to estimate concentrations in the animal products consumed by people motivated the creation of methods to estimate these parameters. For organic chemicals, the transfer factors for beef, milk, and eggs were estimated from the octanol-water partition coefficient (K_{OW}) of the chemical using formulas presented by McKone (1994). Values for Log K_{OW} are given in Table A3. Numbers for the accumulation of organic chemicals in fish were obtained from the EPI Suite software version 3.10.

$$F_{BEEF} = (2.5 \times 10^{-8})\ K_{OW}$$

$$F_{MILK} = (7.9 \times 10^{-9})\ K_{OW}$$

$$F_{EGG} = (8.0 \times 10^{-6})\ K_{OW}$$

For inorganic chemicals, the transfer coefficients are obtained from Table A33. No method was found to estimate the transfer of organic chemicals into poultry. The missing values were assigned values of zero for the calculations of unit risk factors. It is assumed that the poultry contribution to the total hazard index or cancer risk is small because poultry is only considered along with beef, milk, and eggs. The list of equilibrium transfer factors for the chemicals of interest in the representative animal products is shown in Table A35.

Table A35. Transfer Factors for Chemicals into Cows, Chickens, and Fish.

CASRN	Chemical	Beef (d/kg)	Milk (d/kg)	Poultry (d/kg)	Eggs (d/kg)	Fish (L/kg)
50-32-8	Benzo[a]pyrene	3.37E-02	1.07E-02	na	1.08E+01	1.05E+04
53-70-3	Dibenz[a,h]anthracene	1.41E-01	4.44E-02	na	4.50E+01	3.14E+04
56-23-5	Carbon tetrachloride	1.69E-05	5.34E-06	na	5.41E-03	3.01E+01
57-12-5	Cyanide, free	1.41E-08	4.44E-09	na	4.50E-06	3.16E+00
57-14-7	1,1-Dimethylhydrazine	1.61E-09	5.10E-10	na	5.17E-07	3.16E+00
57-55-6	Propylene glycol (1,2-Propanediol)	3.01E-09	9.50E-10	na	9.62E-07	3.16E+00
58-89-9	gamma-Benzene hexachloride (gamma-Lindane)	1.31E-04	4.15E-05	na	4.20E-02	1.46E+02
60-34-4	Methylhydrazine	2.23E-09	7.04E-10	na	7.13E-07	3.16E+00
60-57-1	Dieldrin	6.28E-03	1.98E-03	na	2.01E+00	2.87E+03
62-75-9	N-Nitrosodimethylamine	6.73E-09	2.13E-09	na	2.15E-06	3.16E+00
64-18-6	Formic acid	7.21E-09	2.28E-09	na	2.31E-06	3.16E+00
67-56-1	Methanol (Methyl alcohol)	4.25E-09	1.34E-09	na	1.36E-06	3.16E+00
67-64-1	Acetone (2-Propanone)	1.44E-08	4.55E-09	na	4.60E-06	3.16E+00
67-66-3	Chloroform	2.33E-06	7.37E-07	na	7.47E-04	6.56E+00
71-36-3	n-Butyl alcohol (n-Butanol)	1.90E-07	5.99E-08	na	6.07E-05	3.16E+00
71-43-2	Benzene	3.37E-06	1.07E-06	na	1.08E-03	8.71E+00
71-55-6	1,1,1-Trichloroethane (Methyl chloroform)	7.73E-06	2.44E-06	na	2.47E-03	1.65E+01
72-20-8	Endrin	3.96E-03	1.25E-03	na	1.27E+00	2.01E+03
74-83-9	Bromomethane	3.87E-07	1.22E-07	na	1.24E-04	1.65E+00
74-87-3	Methyl chloride (Chloromethane)	2.03E-07	6.42E-08	na	6.50E-05	3.16E+00
75-00-3	Ethyl Chloride	6.73E-07	2.13E-07	na	2.15E-04	2.52E+00
75-01-4	Vinyl chloride (Chloroethene)	1.04E-06	3.29E-07	na	3.33E-04	3.53E+00
75-05-8	Acetonitrile	1.14E-08	3.61E-09	na	3.66E-06	3.16E+00

Table A35. Transfer Factors for Chemicals into Cows, Chickens, and Fish.

CASRN	Chemical	Beef (d/kg)	Milk (d/kg)	Poultry (d/kg)	Eggs (d/kg)	Fish (L/kg)
75-07-0	Acetaldehyde	1.14E-08	3.61E-09	na	3.66E-06	3.16E+00
75-09-2	Dichloromethane (Methylene chloride)	4.45E-07	1.40E-07	na	1.42E-04	1.83E+00
75-15-0	Carbon disulfide	2.18E-06	6.88E-07	na	6.97E-04	6.22E+00
75-21-8	Ethylene Oxide (Oxirane)	1.25E-08	3.96E-09	na	4.01E-06	3.16E+00
75-34-3	1,1-Dichloroethane (Ethylidene chloride)	1.54E-06	4.87E-07	na	4.93E-04	4.77E+00
75-35-4	1,1-Dichloroethylene	3.37E-06	1.07E-06	na	1.08E-03	8.71E+00
75-45-6	Chlorodifluoromethane	3.01E-07	9.50E-08	na	9.62E-05	1.35E+00
75-68-3	Chloro-1,1-difluoroethane, 1-	2.81E-06	8.86E-07	na	8.98E-04	7.56E+00
75-69-4	Trichlorofluoromethane	8.47E-06	2.68E-06	na	2.71E-03	1.77E+01
75-71-8	Dichlorodifluoromethane	3.61E-06	1.14E-06	na	1.16E-03	9.19E+00
76-13-1	1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113)	3.61E-05	1.14E-05	na	1.16E-02	5.41E+01
76-44-8	Heptachlor	3.15E-02	9.95E-03	na	1.01E+01	9.93E+03
78-87-5	1,2-Dichloropropane	2.39E-06	7.54E-07	na	7.64E-04	6.68E+00
78-93-3	Methyl ethyl ketone (2-Butanone)	4.87E-08	1.54E-08	na	1.56E-05	3.16E+00
79-00-5	1,1,2-Trichloroethane	1.94E-06	6.13E-07	na	6.21E-04	5.69E+00
79-01-6	Trichloroethylene	6.58E-06	2.08E-06	na	2.10E-03	1.46E+01
79-10-7	2-Propenoic acid (Acrylic acid)	5.60E-08	1.77E-08	na	1.79E-05	3.16E+00
79-34-5	1,1,2,2-Tetrachloroethane (Acetylene tetrachloride)	6.14E-06	1.94E-06	na	1.96E-03	1.38E+01
82-68-8	Pentachloronitrobenzene (PCNB)	1.09E-03	3.45E-04	na	3.49E-01	7.46E+02
83-32-9	Acenaphthene	2.08E-04	6.57E-05	na	6.65E-02	2.08E+02
84-66-2	Diethyl phthalate	6.58E-06	2.08E-06	na	2.10E-03	1.46E+01
84-74-2	Dibutyl phthalate	7.91E-04	2.50E-04	na	2.53E-01	5.82E+02
85-68-7	Butyl benzyl phthalate	1.34E-03	4.24E-04	na	4.30E-01	8.75E+02
87-68-3	Hexachlorobutadiene	1.51E-03	4.76E-04	na	4.82E-01	9.56E+02
87-86-5	Pentachlorophenol	3.30E-03	1.04E-03	na	1.05E+00	6.96E+02
88-06-2	2,4,6-Trichlorophenol	1.22E-04	3.87E-05	na	3.92E-02	5.51E+01
88-85-7	2-sec-Butyl-4,6-dinitrophenol (Dinoseb)	9.08E-05	2.87E-05	na	2.90E-02	1.10E+02
91-20-3	Naphthalene	4.99E-05	1.58E-05	na	1.60E-02	6.93E+01
92-52-4	1,1'-Biphenyl	2.39E-04	7.54E-05	na	7.64E-02	2.32E+02
95-50-1	1,2-Dichlorobenzene (ortho-)	6.73E-05	2.13E-05	na	2.15E-02	8.73E+01
95-63-6	1,2,4-Trimethylbenzene	1.07E-04	3.37E-05	na	3.41E-02	1.24E+02
98-86-2	Acetophenone	9.50E-07	3.00E-07	na	3.04E-04	4.75E-01
98-95-3	Nitrobenzene	1.77E-06	5.59E-07	na	5.66E-04	5.30E+00
100-25-4	1,4-Dinitrobenzene (para-)	7.21E-07	2.28E-07	na	2.31E-04	2.66E+00
100-41-4	Ethyl benzene	3.53E-05	1.12E-05	na	1.13E-02	5.31E+01
100-42-5	Styrene	2.23E-05	7.04E-06	na	7.13E-03	3.73E+01
100-51-6	Benzyl alchohol	3.15E-07	9.95E-08	na	1.01E-04	3.14E-01
106-46-7	1,4-Dichlorobenzene (para-)	6.89E-05	2.18E-05	na	2.20E-02	8.89E+01
106-93-4	1,2-Dibromoethane (Ethylene dibromide)	2.28E-06	7.20E-07	na	7.30E-04	6.44E+00
106-99-0	1,3-Butadiene	2.44E-06	7.72E-07	na	7.82E-04	6.80E+00
107-02-8	Acrolein	2.44E-08	7.72E-09	na	7.82E-06	3.16E+00
107-05-1	3-Chloropropene (Allyl chloride)	2.13E-06	6.72E-07	na	6.81E-04	6.11E+00
107-06-2	1,2-Dichloroethane (Ethylene chloride)	7.55E-07	2.39E-07	na	2.42E-04	2.75E+00
107-13-1	Acrylonitrile	4.45E-08	1.40E-08	na	1.42E-05	3.16E+00

Table A35. Transfer Factors for Chemicals into Cows, Chickens, and Fish.

CASRN	Chemical	Beef (d/kg)	Milk (d/kg)	Poultry (d/kg)	Eggs (d/kg)	Fish (L/kg)
108-10-1	Methyl isobutyl ketone (4-Methyl-2-pentanone)	5.10E-07	1.61E-07	na	1.63E-04	2.04E+00
108-67-8	1,3,5-Trimethylbenzene	6.58E-05	2.08E-05	na	2.10E-02	8.58E+01
108-87-2	Methyl cyclohexane	1.02E-04	3.22E-05	na	3.26E-02	1.20E+02
108-88-3	Toluene (Methyl benzene)	1.34E-05	4.24E-06	na	4.30E-03	2.52E+01
108-90-7	Chlorobenzene	1.73E-05	5.47E-06	na	5.53E-03	3.07E+01
108-94-1	Cyclohexanone	1.61E-07	5.10E-08	na	5.17E-05	3.16E+00
108-95-2	Phenol (Carbolic acid)	7.21E-07	2.28E-07	na	2.31E-04	2.66E+00
110-00-9	Furan (Oxacyclopentadiene)	5.47E-07	1.73E-07	na	1.75E-04	2.15E+00
110-54-3	n-Hexane	1.99E-04	6.28E-05	na	6.35E-02	2.01E+02
110-86-1	Pyridine	1.12E-07	3.53E-08	na	3.57E-05	3.16E+00
111-76-2	2-Butoxyethanol (Ethylene Glycol Monobutyl Ether)	1.69E-07	5.34E-08	na	5.41E-05	3.16E+00
111-90-0	2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether)	7.21E-09	2.28E-09	na	2.31E-06	3.16E+00
117-81-7	Di (2-ethylhexyl) phthalate (DEHP)	9.95E-01	3.15E-01	na	3.18E+02	3.08E+02
117-84-0	Di-n-octylphthalate	3.15E+00	9.95E-01	na	1.01E+03	6.35E+01
118-74-1	Hexachlorobenzene	1.34E-02	4.24E-03	na	4.30E+00	5.15E+03
120-82-1	1,2,4-Trichlorobenzene	2.62E-04	8.27E-05	na	8.38E-02	2.49E+02
121-44-8	Triethylamine	7.05E-07	2.23E-07	na	2.25E-04	2.61E+00
122-39-4	Diphenylamine	7.91E-05	2.50E-05	na	2.53E-02	9.89E+01
123-91-1	1,4-Dioxane (Diethylene oxide)	1.34E-08	4.24E-09	na	4.30E-06	3.16E+00
126-73-8	Tributyl Phosphate	2.50E-04	7.90E-05	na	8.00E-02	3.98E+01
126-98-7	2-Methyl-2-propenenitrile (Methacrylonitrile)	1.20E-07	3.78E-08	na	3.83E-05	3.16E+00
127-18-4	1,1,2,2-Tetrachloroethylene	6.28E-05	1.98E-05	na	2.01E-02	8.28E+01
141-78-6	Ethyl acetate (Acetic acid, ethyl ester)	1.34E-07	4.24E-08	na	4.30E-05	3.16E+00
156-59-2	cis-1,2-Dichloroethylene	1.81E-06	5.72E-07	na	5.80E-04	5.40E+00
206-44-0	Fluoranthene (1,2-Benzacenaphthene)	3.61E-03	1.14E-03	na	1.16E+00	1.88E+03
309-00-2	Aldrin	7.91E-02	2.50E-02	na	2.53E+01	2.02E+04
319-84-6	alpha-Benzene hexachloride (alpha-Lindane)	1.58E-04	4.98E-05	na	5.05E-02	1.68E+02
319-85-7	beta-Benzene hexachloride (beta-Lindane)	1.51E-04	4.76E-05	na	4.82E-02	1.62E+02
621-64-7	N-Nitrosodi-N-propylamine	5.73E-07	1.81E-07	na	1.83E-04	2.22E+00
1314-62-1	Vanadium pentoxide	2.50E-03	2.00E-05	2.00E-01	8.00E-01	2.00E+02
1330-20-7	Xylenes (mixtures)	3.30E-05	1.04E-05	na	1.05E-02	5.04E+01
1336-36-3	Polychlorinated Biphenyls (high risk)	4.87E-02	1.54E-02	na	1.56E+01	5.80E+04
1336-36-3	Polychlorinated Biphenyls (low risk)	4.87E-02	1.54E-02	na	1.56E+01	5.80E+04
1336-36-3	Polychlorinated Biphenyls (lowest risk)	4.87E-02	1.54E-02	na	1.56E+01	5.80E+04
6533-73-9	Thallium carbonate	4.00E-02	2.00E-03	3.00E-01	8.00E-01	1.00E+04
7429-90-5	Aluminum	1.50E-03	2.00E-04	3.00E-01	8.00E-01	5.00E+02
7439-96-5	Manganese	5.00E-04	3.00E-05	5.00E-02	6.00E-02	4.00E+02
7439-98-7	Molybdenum	1.00E-03	1.70E-03	1.00E+00	9.00E-01	1.00E+01
7440-02-0	Nickel (soluble salts)	5.00E-03	1.60E-02	1.00E-03	1.00E-01	1.00E+02
7440-22-4	Silver	3.00E-03	5.00E-05	2.00E+00	5.00E-01	5.00E+00
7440-24-6	Strontium, Stable	8.00E-03	2.80E-03	8.00E-02	2.00E-01	6.00E+01
7440-31-5	Tin	8.00E-02	1.00E-03	2.00E-01	8.00E-01	3.00E+03

Table A35. Transfer Factors for Chemicals into Cows, Chickens, and Fish.

CASRN	Chemical	Beef (d/kg)	Milk (d/kg)	Poultry (d/kg)	Eggs (d/kg)	Fish (L/kg)
7440-36-0	Antimony	4.00E-05	2.50E-05	6.00E-03	7.00E-02	1.00E+02
7440-38-2	Arsenic (inorganic)	2.00E-03	6.00E-05	8.30E-01	8.00E-01	2.44E+02
7440-39-3	Barium	2.00E-04	4.80E-04	9.00E-03	9.00E-01	4.00E+00
7440-41-7	Beryllium and compounds	1.00E-03	9.00E-07	4.00E-01	2.00E-02	1.00E+02
7440-42-8	Boron and borates only	8.00E-04	1.50E-03	2.00E-01	8.00E-01	5.00E+00
7440-43-9	Cadmium	4.00E-04	1.00E-03	8.00E-01	1.00E-01	2.00E+02
7440-48-4	Cobalt	1.00E-02	3.00E-04	2.00E+00	1.00E-01	3.00E+02
7440-66-6	Zinc and compounds	1.00E-01	1.00E-02	7.00E+00	3.00E+00	2.52E+02
7487-94-7	Mercuric chloride	2.50E-01	4.70E-04	3.00E-02	2.00E-01	1.00E+03
7664-41-7	Ammonia	1.04E-09	3.29E-10	na	3.33E-07	3.16E+00
7723-14-0	Phosphorus, white	5.00E-02	1.60E-02	1.90E-01	1.00E+01	1.50E+03
7782-41-4	Fluorine (soluble fluoride)	1.50E-01	1.00E-03	1.00E-02	2.00E+00	1.00E+01
7782-49-2	Selenium and compounds	1.50E-02	4.00E-03	9.00E+00	9.00E+00	1.70E+02
8001-35-2	Toxaphene	1.51E-02	4.76E-03	na	4.82E+00	5.63E+03
14797-55-8	Nitrate	na	na	na	na	3.16E+00
14797-65-0	Nitrite	na	na	na	na	3.16E+00
16065-83-1	Chromium (III) (insoluble salts)	9.00E-03	1.00E-05	2.00E-01	8.00E-01	2.00E+02
18540-29-9	Chromium (VI) (soluble salts)	9.00E-03	1.00E-05	2.00E-01	8.00E-01	2.00E+02
none	Uranium (soluble salts)	3.00E-04	4.00E-04	1.00E+00	1.00E+00	1.00E+01

Notes:

- CASRN = Chemical Abstract Service Reference Number
- The transfer factors into beef, milk, and eggs for organic chemicals are calculated from the octanol-water coefficients in Table A3. The numbers for fish are from the EPI Suite software version 3.10. All numbers for the inorganic chemicals are from Table A32.
- Missing values are indicated with “na”, which means “not available”.

A5.0 PLANT PARAMETERS

Living plants eaten by people fall into two broad categories, aquatic plants and terrestrial plants. It will be assumed that aquatic plants contribute very little to the typical human diet. If exceptions are identified then a suitable set of parameters and models for contaminant uptake by aquatic plants and subsequent consumptions by humans will be utilized. All plants eaten are assumed to be terrestrial rather than aquatic.

The calculation of radionuclide concentrations in living terrestrial plants uses three main routes, (1) root uptake, (2) resuspension to leaves (also called "rain splash"), and (3) direct deposition of irrigation water on foliage. Each of these will be considered separately below. The three uptake routes are then combined to obtain the total concentration in edible portions of plants.

A5.1 Root Uptake

The model for root uptake of a contaminant into terrestrial plants assumes that the concentration in the edible portion is proportional to the concentration in the soil at the time of harvest. The constants of proportionality are known as the soil-to-plant concentration ratios. These concentration ratios are measured as the concentration of the dry produce item divided by the soil concentration. They have no units, since the soil and food items have the same mass-based concentration units, e.g., pCi/kg.

Because the human consumption rates for plants shown in Table A4 are the wet weights, it is necessary to select suitable constants to convert to dry weight. These constants are known as "dry-to-wet ratios". They are simply the dry weight of the food item divided by the wet weight of the item. The "dry-to-wet ratios" from three sources are listed in Table A36. The values chosen for the tank waste PA are from PNWD-2023 for leafy vegetables and NUREG/CR-5512 for the others. The chosen values for the tank waste PA appear in the last column of Table A36. The values under the "GENII" column have been used in prior Hanford Site performance assessments.

Table A36. Dry-to-Wet Ratios for Vegetation Consumed by Humans.

Type of Produce	GENII	ORNL-5786	Tank Waste PA
Leafy Vegetables	0.10	0.067	0.09
Other (protected)	0.25	0.222	0.25
Fruit (exposed)	0.18	0.126	0.18
Grains	0.18	0.888	0.91

The tank waste PA values are from PNWD-2023 and NUREG/CR-5512.
The dry-to-wet ratio used for uptake of chemicals is 0.2 based on the weighted sum of the above values. The weighting factors are the mass of each type of vegetation consumed annually. Note that grains are not irrigated and therefore not included in the weighed sum.

The GENII dry-to-wet ratios for grains differ greatly from the other collections. However, it has been assumed in prior performance assessments that grains would be unlikely to become contaminated in the intruder or irrigation scenarios. The intruder would probably not raise grains in his home garden, and the principal grain crop in this area (dry-land wheat) would not be irrigated. For the tank waste PA, grains are not included as contaminated vegetable intakes.

Root uptake for radionuclides will be calculated using concentration ratios listed in Table A37. The ratios for four types of vegetables are given on this table. The definition of the four types was presented with the consumption rates and will not be repeated here. The value for the iodine concentration ratio in leafy vegetables is from the more recent HEDR assessment (PNWD-2023 1994). The values for hydrogen were calculated using an equilibrium assumption. The ratio of tritium to hydrogen in the soil is assumed to also exist in the plant. Thus, the effective soil-to-plant transfer factor is the hydrogen concentration in the plant divided by the hydrogen concentration in the soil and the dry-to-wet ratio for the plant.

The soil-to-plant concentration ratios were selected using the following hierarchy: PNWD-2023, IAEA Technical Report Number 364, ORNL-5786, and NUREG/CR-5512. The letter next to the number in Table A37 shows the source for each number.

The transfer factors for manganese (Mn), cobalt (Co), and technetium (Tc) into leafy vegetables from IAEA Technical Report Number 364, are the weighted sum of concentration ratios for cabbage, lettuce, and spinach. The weighting is based on the USDA consumption rates found in Statistical Bulletin Number 965 (1999). In this bulletin the average individual eats

10.6 lb cabbage, 28.2 lb lettuce, and 0.5 lb of spinach annually. In terms of percentages these correspond to 27.0%, 71.8%, and 1.3%. The mean transfer factors for cabbage, lettuce and spinach were multiplied by these percentages to arrive at the weighted transfer factor.

Table A37. Transfer Factors for Radionuclides into Plants.

Element	Plant/Soil Concentration Ratios (dry)				Atomic Number
	Leafy	Root	Fruit	Grain	
H	na	na	na	na	1
Be	0.010 c	1.5E-03 c	1.5E-03 c	1.5E-03 c	4
B	4.0 c	2.0 c	2.0 c	2.0 c	5
C	0.70 d	0.70 d	0.70 d	0.70 d	6
F	0.060 c	6.0E-03 c	6.0E-03 c	6.0E-03 c	9
Na	0.30 b	0.30 b	0.30 b	0.30 b	11
Al	4.0E-03 c	6.5E-04 c	6.5E-04 c	6.5E-04 c	13
Si	0.35 c	0.070 c	0.070 c	0.070 c	14
P	3.5 c	3.5 c	3.5 c	3.5 c	15
Cl	70 c	70 c	70 c	70 c	17
K	1.0 c	0.55 c	0.55 c	0.55 c	19
Ca	3.5 c	0.35 c	0.35 c	0.35 c	20
Ti	5.5E-03 c	3.0E-03 c	3.0E-03 c	3.0E-03 c	22
V	5.5E-03 c	3.0E-03 c	3.0E-03 c	3.0E-03 c	23
Mn	0.69 b	0.28 b	0.19 b	0.30 b	25
Fe	4.0E-03 b	4.0E-03 b	4.0E-03 b	4.0E-03 b	26
Co	0.22 b	0.068 b	7.0E-03 c	3.7E-03 b	27
Ni	0.060 c	0.060 c	0.060 c	0.030 b	28
As	0.040 c	6.0E-03 c	6.0E-03 c	6.0E-03 c	33
Se	0.025 c	0.025 c	0.025 c	0.025 c	34
Rb	0.90 b	0.90 b	0.90 b	0.90 b	37
Sr	3.0 b	0.61 b	0.20 b	0.21 b	38
Y	0.010 b	0.010 b	0.010 b	0.010 b	39
Zr	1.0E-03 b	1.0E-03 b	1.0E-03 b	1.0E-03 b	40
Nb	0.017 b	0.017 b	0.017 b	0.017 b	41
Mo	0.80 b	0.80 b	0.80 b	0.80 b	42
Tc	180 b	0.77 b	1.5 c	0.73 b	43
Ru	0.20 b	0.040 b	0.040 b	5.0E-03 b	44
Pd	0.15 c	0.040 c	0.040 c	0.040 c	46
Ag	2.7E-04 b	1.3E-03 b	8.0E-04 b	0.15 b	47
Cd	0.55 c	0.15 c	0.15 c	0.15 c	48
In	4.0E-03 c	4.0E-04 c	4.0E-04 c	4.0E-04 c	49
Sn	0.030 c	6.0E-03 c	6.0E-03 c	6.0E-03 c	50
Sb	0.20 c	5.6E-04 b	0.030 c	0.030 c	51
Te	0.025 c	4.0E-03 c	4.0E-03 c	4.0E-03 c	52
I	0.050 a	0.020 b	0.020 b	0.020 b	53
Cs	0.46 b	0.13 b	0.22 b	0.026 b	55
Ba	0.15 c	0.030 b	0.030 b	0.030 b	56
Pm	0.010 c	4.0E-03 c	4.0E-03 c	4.0E-03 c	61
Sm	0.010 c	4.0E-03 c	4.0E-03 c	4.0E-03 c	62
Eu	0.010 c	4.0E-03 c	4.0E-03 c	4.0E-03 c	63
Gd	0.010 c	4.0E-03 c	4.0E-03 c	4.0E-03 c	64

Table A37. Transfer Factors for Radionuclides into Plants.

Element	Plant/Soil Concentration Ratios (dry)				Atomic Number
	Leafy	Root	Fruit	Grain	
Ho	0.010 c	4.0E-03 c	4.0E-03 c	4.0E-03 c	67
Re	1.5 c	0.35 c	0.35 c	0.35 c	75
Hg	0.90 c	0.20 c	0.20 c	0.20 c	80
Tl	4.0E-03 c	4.0E-04 c	4.0E-04 c	4.0E-04 c	81
Pb	0.010 b	6.2E-03 b	9.0E-03 c	4.7E-03 b	82
Bi	0.035 c	5.0E-03 c	5.0E-03 c	5.0E-03 c	83
Po	1.2E-03 b	7.0E-03 b	4.0E-04 c	2.3E-03 b	84
Ra	0.049 b	2.5E-03 b	6.1E-03 b	1.2E-03 b	88
Ac	3.5E-03 c	3.5E-04 c	3.5E-04 c	3.5E-04 c	89
Th	1.8E-03 b	2.5E-04 b	8.5E-05 c	3.4E-05 b	90
Pa	2.5E-03 c	2.5E-04 c	2.5E-04 c	2.5E-04 c	91
U	8.3E-03 b	0.012 b	4.0E-03 c	1.3E-03 b	92
Np	0.037 b	0.014 b	0.010 c	2.7E-03 b	93
Pu	6.0E-05 b	5.8E-04 b	9.0E-05 b	8.6E-06 b	94
Am	4.3E-04 b	4.1E-04 b	2.5E-04 c	2.2E-05 b	95
Cm	7.7E-04 b	4.6E-04 b	1.5E-05 c	2.1E-05 b	96
Bk	4.3E-04 b	4.1E-04 b	2.5E-04 c	2.2E-05 b	97
Cf	0.010 d	0.010 d	0.010 d	0.010 d	98

Notes:

- These parameters were selected using the following hierarchy: (a) PNWD-2023, (b) IAEA Technical Report Number 364, (c) ORNL-5786, and (d) NUREG/CR-5512. The values for Leafy and Root in IAEA #364 are weighted sums of leafy or protected crops discussed in the text.
- Transfer factors for Bk are assumed to be the same as Am.
- Transfer factors for hydrogen are not shown (na) because a different model is used to calculate tritium concentrations in plants.

Similarly, for several nuclides in IAEA Technical Report Number 364 the transfer factors into root vegetables are the weighted sum of concentration ratios for root vegetables (i.e., onions, carrots, radishes, potatoes, pods, corn, and other crops). The weighting is based on the USDA consumption rates found in Statistical Bulletin Number 965 (1999). In this bulletin the average individual eats 16.8 lb onions, 12.1 lb carrots, 0.4 lb radishes, 82.9 lb potatoes, 3.5 lb pods, 7.4 lb corn, and 67.5 lb others annually. The mean transfer factors for the root crops that are listed in the IAEA report are weighted by these consumption rates to arrive at the weighted transfer factor shown in Table A37. The elements for which this was carried out are manganese (Mn), cobalt (Co), zinc (Zn), strontium (Sr), technetium (Tc), cesium (Cs), lead (Pb), radium (Ra), thorium (Th), uranium (U), neptunium (Np), plutonium (Pu), americium (Am), and curium (Cm).

Concentration ratios for berkelium (Bk) were assumed to be the same as those for americium (Am), because none of the references supplied any values for berkelium.

Animal fodder is not shown separately in Table A37. Pasture grass (fresh) and hay (stored) are represented using the transfer factors for leafy vegetables. The stored grain is represented using the factors for grain.

Root uptake for chemicals into plants will be calculated using concentration ratios listed in Table A38. The ratios for just one type of plant are given on this table. The concentration ratios for organic chemicals are from the octanol-water constants shown in Table A3. The formula used to calculate the soil-to-plant (wet) factors is from McKone (1994) and is shown below. The factors for the dry plant are calculated by dividing the wet plant numbers by the dry-to-wet ratio, 0.2 from Table A36.

$$F_{PLANTS} = 7.7 \ (K_{OW})^{-0.58}$$

The concentration ratios for the inorganic chemicals are obtained from Table A37. The concentration ratios for the four plant types were combined into one using the USDA consumption amounts shown in Table A4 and the dry-to-wet ratios shown in Table A36. Grains were omitted from the weighting because they are assumed to have no contaminated irrigation water. For this generic garden crop a dry-to-wet ratio of 0.2 is assumed.

Table A38. Transfer Factors for Chemicals into Garden Produce, and Leaching from the Surface Soil.

CASRN	Chemical	Soil-to-Plant (dry) Transfer Factor	Leaching Factor (per year)	Soil-Water Partition Coefficient	Organic Carbon Partition Coefficient
50-32-8	Benzo[a]pyrene	1.06E-02	1.88E-05	2.36E+04	7.87E+05
53-70-3	Dibenz[a,h]anthracene	4.62E-03	5.65E-06	7.87E+04	2.62E+06
56-23-5	Carbon tetrachloride	8.68E-01	2.79E-01	1.46E+00	4.86E+01
57-12-5	Cyanide, free	5.31E+01	4.43E-02	9.90E+00	2.71E+00
57-14-7	1,1-Dimethylhydrazine	1.86E+02	6.12E-01	5.93E-01	1.98E+01
57-55-6	Propylene glycol (1,2-Propanediol)	1.30E+02	2.72E+00	3.00E-02	1.00E+00
58-89-9	gamma-Benzene hexachloride (gamma-Lindane)	2.64E-01	4.38E-03	1.01E+02	3.38E+03
60-34-4	Methylhydrazine	1.54E+02	6.65E-01	5.35E-01	1.78E+01
60-57-1	Dieldrin	2.80E-02	1.40E-03	3.18E+02	1.06E+04
62-75-9	N-Nitrosodimethylamine	8.14E+01	3.47E-01	1.15E+00	3.82E+01
64-18-6	Formic acid	7.82E+01	2.72E+00	3.00E-02	1.00E+00
67-56-1	Methanol (Methyl alcohol)	1.06E+02	2.72E+00	3.00E-02	1.00E+00
67-64-1	Acetone (2-Propanone)	5.24E+01	2.31E+00	5.94E-02	1.98E+00
67-66-3	Chloroform	2.74E+00	3.75E-01	1.05E+00	3.50E+01
71-36-3	n-Butyl alcohol (n-Butanol)	1.17E+01	2.15E+00	7.33E-02	2.44E+00
71-43-2	Benzene	2.21E+00	8.72E-02	4.97E+00	1.66E+02
71-55-6	1,1,1-Trichloroethane (Methyl chloroform)	1.37E+00	2.79E-01	1.46E+00	4.86E+01
72-20-8	Endrin	3.66E-02	1.40E-03	3.18E+02	1.06E+04
74-83-9	Bromomethane	7.76E+00	7.90E-01	4.29E-01	1.43E+01
74-87-3	Methyl chloride (Chloromethane)	1.13E+01	7.90E-01	4.29E-01	1.43E+01
75-00-3	Ethyl Chloride	5.63E+00	5.26E-01	7.12E-01	2.37E+01
75-01-4	Vinyl chloride (Chloroethene)	4.37E+00	5.26E-01	7.12E-01	2.37E+01
75-05-8	Acetonitrile	5.98E+01	1.66E+00	1.35E-01	4.50E+00
75-07-0	Acetaldehyde	5.98E+01	2.49E+00	4.49E-02	1.50E+00
75-09-2	Dichloromethane (Methylene chloride)	7.16E+00	5.26E-01	7.12E-01	2.37E+01
75-15-0	Carbon disulfide	2.85E+00	2.72E+00	3.00E-02	1.00E+00
75-21-8	Ethylene Oxide (Oxirane)	5.67E+01	2.52E+00	4.31E-02	1.44E+00

Table A38. Transfer Factors for Chemicals into Garden Produce, and Leaching from the Surface Soil.

CASRN	Chemical	Soil-to-Plant (dry) Transfer Factor	Leaching Factor (per year)	Soil-Water Partition Coefficient	Organic Carbon Partition Coefficient
75-34-3	1,1-Dichloroethane (Ethylidene chloride)	3.48E+00	3.75E-01	1.05E+00	3.50E+01
75-35-4	1,1-Dichloroethylene	2.21E+00	3.75E-01	1.05E+00	3.50E+01
75-45-6	Chlorodifluoromethane	8.98E+00	3.75E-01	1.05E+00	3.50E+01
75-68-3	Chloro-1,1-difluoroethane, 1-	2.46E+00	2.79E-01	1.46E+00	4.86E+01
75-69-4	Trichlorofluoromethane	1.30E+00	2.79E-01	1.46E+00	4.86E+01
75-71-8	Dichlorodifluoromethane	2.12E+00	2.79E-01	1.46E+00	4.86E+01
76-13-1	1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113)	5.58E-01	6.47E-02	6.74E+00	2.25E+02
76-44-8	Heptachlor	1.10E-02	2.83E-04	1.57E+03	5.24E+04
78-87-5	1,2-Dichloropropane	2.70E+00	2.05E-01	2.03E+00	6.77E+01
78-93-3	Methyl ethyl ketone (2-Butanone)	2.58E+01	1.79E+00	1.15E-01	3.83E+00
79-00-5	1,1,2-Trichloroethane	3.04E+00	2.05E-01	2.03E+00	6.77E+01
79-01-6	Trichloroethylene	1.50E+00	2.05E-01	2.03E+00	6.77E+01
79-10-7	2-Propenoic acid (Acrylic acid)	2.38E+01	2.62E+00	3.60E-02	1.20E+00
79-34-5	1,1,2,2-Tetrachloroethane (Acetylene tetrachloride)	1.56E+00	1.33E-01	3.20E+00	1.07E+02
82-68-8	Pentachloronitrobenzene (PCNB)	7.74E-02	6.15E-03	7.22E+01	2.41E+03
83-32-9	Acenaphthene	2.02E-01	2.42E-03	1.84E+02	6.12E+03
84-66-2	Diethyl phthalate	1.50E+00	1.13E-01	3.79E+00	1.26E+02
84-74-2	Dibutyl phthalate	9.33E-02	1.01E-02	4.38E+01	1.46E+03
85-68-7	Butyl benzyl phthalate	6.86E-02	1.58E-03	2.81E+02	9.36E+03
87-68-3	Hexachlorobutadiene	6.42E-02	1.48E-02	2.98E+01	9.94E+02
87-86-5	Pentachlorophenol	4.08E-02	4.38E-03	1.01E+02	3.38E+03
88-06-2	2,4,6-Trichlorophenol	2.75E-01	1.24E-02	3.56E+01	1.19E+03
88-85-7	2-sec-Butyl-4,6-dinitrophenol (Dinoseb)	3.27E-01	4.18E-03	1.06E+02	3.54E+03
91-20-3	Naphthalene	4.63E-01	8.05E-03	5.51E+01	1.84E+03
92-52-4	1,1'-Biphenyl	1.87E-01	2.37E-03	1.88E+02	6.25E+03
95-50-1	1,2-Dichlorobenzene (ortho-)	3.89E-01	3.31E-02	1.33E+01	4.43E+02
95-63-6	1,2,4-Trimethylbenzene	2.98E-01	2.05E-02	2.15E+01	7.18E+02
98-86-2	Acetophenone	4.61E+00	2.93E-01	1.39E+00	4.62E+01
98-95-3	Nitrobenzene	3.21E+00	7.59E-02	5.72E+00	1.91E+02
100-25-4	1,4-Dinitrobenzene (para-)	5.41E+00	6.60E-02	6.60E+00	2.20E+02
100-41-4	Ethyl benzene	5.66E-01	2.84E-02	1.55E+01	5.18E+02
100-42-5	Styrene	7.39E-01	2.84E-02	1.55E+01	5.18E+02
100-51-6	Benzyl alchohol	8.75E+00	7.37E-01	4.70E-01	1.57E+01
106-46-7	1,4-Dichlorobenzene (para-)	3.84E-01	3.38E-02	1.30E+01	4.34E+02
106-93-4	1,2-Dibromoethane (Ethylene dibromide)	2.77E+00	3.07E-01	1.31E+00	4.38E+01
106-99-0	1,3-Butadiene	2.66E+00	3.07E-01	1.31E+00	4.38E+01
107-02-8	Acrolein	3.85E+01	2.06E+00	8.29E-02	2.76E+00
107-05-1	3-Chloropropene (Allyl chloride)	2.89E+00	3.07E-01	1.31E+00	4.38E+01
107-06-2	1,2-Dichloroethane (Ethylene chloride)	5.26E+00	3.07E-01	1.31E+00	4.38E+01
107-13-1	Acrylonitrile	2.72E+01	1.16E+00	2.49E-01	8.30E+00

Table A38. Transfer Factors for Chemicals into Garden Produce, and Leaching from the Surface Soil.

CASRN	Chemical	Soil-to-Plant (dry) Transfer Factor	Leaching Factor (per year)	Soil-Water Partition Coefficient	Organic Carbon Partition Coefficient
108-10-1	Methyl isobutyl ketone (4-Methyl-2-pentanone)	6.61E+00	9.65E-01	3.27E-01	1.09E+01
108-67-8	1,3,5-Trimethylbenzene	3.95E-01	2.09E-02	2.11E+01	7.03E+02
108-87-2	Methyl cyclohexane	3.06E-01	5.44E-02	8.04E+00	2.68E+02
108-88-3	Toluene (Methyl benzene)	9.92E-01	5.44E-02	8.04E+00	2.68E+02
108-90-7	Chlorobenzene	8.56E-01	5.44E-02	8.04E+00	2.68E+02
108-94-1	Cyclohexanone	1.29E+01	7.56E-01	4.55E-01	1.52E+01
108-95-2	Phenol (Carbolic acid)	5.41E+00	5.44E-02	8.04E+00	2.68E+02
110-00-9	Furan (Oxacyclopentadiene)	6.35E+00	1.57E-01	2.69E+00	8.97E+01
110-54-3	n-Hexane	2.08E-01	9.65E-02	4.47E+00	1.49E+02
110-86-1	Pyridine	1.60E+01	3.96E-01	9.90E-01	3.30E+01
111-76-2	2-Butoxyethanol (Ethylene Glycol Monobutyl Ether)	1.25E+01	2.72E+00	3.00E-02	1.00E+00
111-90-0	2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether)	7.82E+01	2.72E+00	3.00E-02	1.00E+00
117-81-7	Di (2-ethylhexyl) phthalate (DEHP)	1.49E-03	8.96E-05	4.96E+03	1.65E+05
117-84-0	Di-n-octylphthalate	7.62E-04	7.58E-05	5.87E+03	1.96E+05
118-74-1	Hexachlorobenzene	1.80E-02	4.38E-03	1.01E+02	3.38E+03
120-82-1	1,2,4-Trichlorobenzene	1.77E-01	2.05E-02	2.15E+01	7.18E+02
121-44-8	Triethylamine	5.48E+00	1.33E-01	3.22E+00	1.07E+02
122-39-4	Diphenylamine	3.55E-01	7.83E-03	5.66E+01	1.89E+03
123-91-1	1,4-Dioxane (Diethylene oxide)	5.45E+01	2.72E+00	3.00E-02	1.00E+00
126-73-8	Tributyl Phosphate	1.82E-01	7.83E-03	5.66E+01	1.89E+03
126-98-7	2-Methyl-2-propenenitrile (Methacrylonitrile)	1.53E+01	8.58E-01	3.85E-01	1.28E+01
127-18-4	1,1,2,2-Tetrachloroethylene	4.05E-01	1.33E-01	3.20E+00	1.07E+02
141-78-6	Ethyl acetate (Acetic acid, ethyl ester)	1.43E+01	1.40E+00	1.84E-01	6.13E+00
156-59-2	cis-1,2-Dichloroethylene	3.17E+00	3.07E-01	1.31E+00	4.38E+01
206-44-0	Fluoranthene (1,2-Benzacenaphthene)	3.86E-02	2.09E-04	2.13E+03	7.09E+04
309-00-2	Aldrin	6.45E-03	1.40E-04	3.17E+03	1.06E+05
319-84-6	alpha-Benzene hexachloride (alpha-Lindane)	2.38E-01	4.38E-03	1.01E+02	3.38E+03
319-85-7	beta-Benzene hexachloride (beta-Lindane)	2.44E-01	4.38E-03	1.01E+02	3.38E+03
621-64-7	N-Nitrosodi-N-propylamine	6.18E+00	3.03E-02	1.46E+01	4.85E+02
1314-62-1	Vanadium pentoxide	3.12E-03	4.44E-04	1.00E+03	1.93E+02
1330-20-7	Xylenes (mixtures)	5.89E-01	3.31E-02	1.33E+01	4.43E+02
1336-36-3	Polychlorinated Biphenyls (high risk)	8.54E-03	3.31E-04	1.34E+03	4.48E+04
1336-36-3	Polychlorinated Biphenyls (low risk)	8.54E-03	3.31E-04	1.34E+03	4.48E+04
1336-36-3	Polychlorinated Biphenyls (lowest risk)	8.54E-03	3.31E-04	1.34E+03	4.48E+04
6533-73-9	Thallium carbonate	5.75E-04	2.96E-04	1.50E+03	8.25E+00
7429-90-5	Aluminum	8.13E-04	2.96E-04	1.50E+03	1.43E+01
7439-96-5	Manganese	2.73E-01	1.85E-04	2.40E+03	1.43E+01
7439-98-7	Molybdenum	8.00E-01	5.90E-02	7.40E+00	1.43E+01
7440-02-0	Nickel (soluble salts)	6.00E-02	1.85E-04	2.40E+03	1.43E+01

Table A38. Transfer Factors for Chemicals into Garden Produce, and Leaching from the Surface Soil.

CASRN	Chemical	Soil-to-Plant (dry) Transfer Factor	Leaching Factor (per year)	Soil-Water Partition Coefficient	Organic Carbon Partition Coefficient
7440-22-4	Silver	1.10E-03	4.93E-03	9.00E+01	1.43E+01
7440-24-6	Strontium, Stable	6.04E-01	2.47E-03	1.80E+02	1.43E+01
7440-31-5	Tin	7.17E-03	4.94E-04	9.00E+02	1.43E+01
7440-36-0	Antimony	1.90E-02	8.89E-05	5.00E+03	1.43E+01
7440-38-2	Arsenic (inorganic)	7.65E-03	2.22E-03	2.00E+02	1.43E+01
7440-39-3	Barium	3.58E-02	7.39E-03	6.00E+01	1.43E+01
7440-41-7	Beryllium and compounds	1.91E-03	1.85E-03	2.40E+02	1.43E+01
7440-42-8	Boron and borates only	2.10E+00	1.42E-01	3.00E+00	1.43E+01
7440-43-9	Cadmium	1.69E-01	6.00E-03	7.40E+01	1.43E+01
7440-48-4	Cobalt	5.72E-02	7.39E-03	6.00E+01	1.43E+01
7440-66-6	Zinc and compounds	2.26E+01	2.22E-03	2.00E+02	1.43E+01
7487-94-7	Mercuric chloride	2.34E-01	4.39E-02	1.00E+01	2.37E+01
7664-41-7	Ammonia	2.40E+02	7.90E-01	4.29E-01	1.43E+01
7723-14-0	Phosphorus, white	3.50E+00	4.87E-02	9.00E+00	1.43E+01
7782-41-4	Fluorine (soluble fluoride)	8.63E-03	2.96E-03	1.50E+02	1.43E+01
7782-49-2	Selenium and compounds	2.50E-02	2.08E-01	2.00E+00	1.43E+01
8001-35-2	Toxaphene	1.69E-02	1.49E-04	2.98E+03	9.93E+04
14797-55-8	Nitrate	na	0.533	0.70	1.43E+01
14797-65-0	Nitrite	na	0.533	0.70	2.37E+01
16065-83-1	Chromium (III) (insoluble salts)	1.00E-03	6.62E-03	6.70E+01	na
18540-29-9	Chromium (VI) (soluble salts)	1.00E-03	0.533	0.70	na
none	Uranium (soluble salts)	9.44E-03	6.23E-02	7.00E+00	na

Notes:

- CASRN = Chemical Abstract Service Reference Number
- The soil-to-plant transfer factors for organic chemicals are from EPI Suite version 3.10. Numbers for the inorganic chemicals are from Table A36.
- Soil-water partition coefficients for organic chemicals were calculated as the product of the organic carbon partition coefficient and the assumed carbon fraction in soil, 3%, from Table A33. Numbers for inorganic chemicals are from Table A40.
- Leaching factors are calculated from the Soil-Water Partition Coefficients as described in Section A6.0.
- Missing values are indicated with "na", which means "not available".

The Hanford Site is very dry and sandy, so that plant uptake factors would likely differ from the generic values listed in Tables A37 and A38. However, the preparation of the soil for a garden changes the properties of surface layer. The tilling, watering and addition of fertilizers and organic material produces soil that resembles the generic garden soil. It is therefore assumed that the concentration ratios in Tables A37 and A38 are adequate to describe plant uptakes in possible future gardens on the Hanford Site.

Groups of people gathering native vegetation for nourishment and other household needs may require special consideration. The soil-to-plant transfer factors for species not usually considered as garden plants growing without cultivation could differ considerably from the values shown on Tables A37 and A38. Soils deficient in some mineral may have much higher uptake factors for materials that are chemically similar to what is missing. The converse is also true. In addition, the distribution of the contaminant in the native vegetation during the growth of the plant is important. For example, Native American Indians use various parts of the cattail over its growth stages (CTUIR 1995). However, the tank waste PA exposure scenarios involve localized areas of contaminated soil resulting from intrusion or irrigation with contaminated ground water. In general, the transfer factors for native plant species are not needed because the contaminated portion would be an insignificant part of the overall diet.

A5.2 Rain Splash

The term "rain splash" refers to all the processes that cause soil to deposit on the surfaces of plants. It includes the transport of soil by the irrigation water, rain drops, and the wind. The standard model (NRC 1977) then includes a "translocation" factor, which is the fraction of activity deposited on plant surfaces that ends up in the edible portions of the plant. There are two basic approaches to estimating the concentration in plants due to resuspension of contaminated soil. The standard approach begins with an estimate of the average air concentration and then computes the activity deposition rate on the plant. The other approach (NUREG/CR-5512 1992) simply treats rain splash in a manner similar to root uptake.

In NUREG/CR-5512, Vol. 1, the amount of rain splash is characterized by a "mass loading" factor, which is the ratio of foliage contamination due to rain splash divided by the concentration in the soil nearby. It is similar to the root uptake concentration ratio described in the previous section. The value recommended in NUREG/CR-5512, Section 6.5.2 is 0.1 Ci/kg (dry produce) per Ci/kg soil for all plant types. In addition, this value "includes consideration of translocation of activity in soil from plant surfaces to edible parts of the plant." The only other parameter used to estimate the actual plant concentration from rain splash is the dry-to-wet ratio. Using a generic dry-to-wet ratio of 0.2 means that about (0.1)(0.2)=2% of the wet mass of the plant comes from attached soil. This large value applies to irrigation methods that involve large water drops and planting methods that leave considerable space between plants even at the time of harvest.

In IAEA Technical Report 364 (1994) the soil adhesion is given a range from 0.010 (short plants) to 0.25 for leafy vegetation. Using a representative dry-to-wet ratio of 0.1 for leafy vegetables means the mass loadings range from 0.1% to 2.5%. In NCRP Report Number 123 Section 5.1, the soil-to-plant concentration ratio has a minimum value of 0.001. In effect this is the soil adhesion term for the wet plant. Thus, the effective mass loading is 0.1%.

In the arid environment of southeastern Washington, irrigation methods that reduce evaporative loss are preferred. This has the effect of lowering the amount of soil transferred to plant surfaces during irrigation. The model used at Hanford and elsewhere (eg., SAND2001-2977) begins with an average air concentration near the plants and computes a deposition rate onto plant surfaces. The RESRAD program (ANL/EAD/LD-2) has a default mass loading air concentration of 0.1 mg/m^3. The default value in GENII is 0.225 mg/m^3. Both of these use a deposition speed of 0.001 m/sec, which is suitable for respirable particles. The resulting deposition rate in RESRAD is 8.64 mg/m^2 per day, while in GENII Version 1.485 it is 19.44 mg/m^2 per day. However, these assumptions lead to rain splash transfers that are two or three orders of magnitude below the experimental data referenced in NUREG/CR-5512, Vol. 1.

For the tank waste PA the customary soil deposition model will be used rather than the effective mass loading approach of NUREG/CR-5512. However, the assumed average deposition rate will be taken to be 270 mg/m^2 per day, which is larger than used in GENII (19.44 mg/m^2 per day), but smaller than was used in the 2001 ILAW PA (864 mg/m^2 per day).

The decrease from the 2001 ILAW PA stems from the fact that irrigation is not continuous, but takes place for a relatively short period (less than 1 hour) every day or so. Thus the average involves large deposition rates during short periods with little deposited between due to the moist conditions. For a small garden, much of the soil that adheres may come from sources of dust outside the garden. The average air concentration of 1 mg/m^3 with a deposition speed of 0.01 m/s used in the 2001 ILAW PA represents conditions during active irrigation. However, the average deposition rate will be some factor lower due to the intermittent nature of the irrigation process.

The increase from the deposition rate used in other performance assessments is based on the need to match the minimum value listed in the IAEA Technical Report Number 364 and NCRP Report Number 123. With a deposition rate of 270 mg/m^2 per day, the mass loading in leafy vegetables is about 0.1%. The calculation is shown below.

$$\frac{J_{SPLASH}\ F_{INT}\ F_{TRANS}\ T_W}{Y_V} = \frac{\left(2.7 \text{ x } 10^{-4} \text{ kg/m}^2 \text{ per day}\right)(0.407)(1.0)(18 \text{ d})}{2.0 \text{ kg/m}^2} = 9.89 \text{ x } 10^{-4}$$

where,

F_{INT}	=	interception fraction for airborne dust on exposed surfaces of leafy vegetables, 0.407, from Table A39
F_{TRANS}	=	translocation factor from exposed surfaces to the edible portion of leafy vegetables, 1.0, from Table A39
J_{SPLASH}	=	average soil deposition rate due to rain splash, 2.7x10^{-4} kg/m^2 per day
T_W	=	effective exposure time for leafy vegetables, 18.0 days, from Table B1. This is derived from a 45-day growing period with a weathering half life of 14 days.
Y_V	=	yield of leafy vegetables, from Table A39, 2.0 kg(wet)/m^2

In particular, the effective wet concentration ratios for leafy, other, fruit, and grains are calculated using the formula shown in Section 3.2 for the post-intrusion resident ingestion dose. The wet ratios are 0.099%, 0.022%, 0.015%, and 0.025% respectively. Since NUREG/CR-5512 recommended a number of about 2%, the model selected for the tank waste PA remains much lower, to some extent consistent with previous Hanford performance assessments.

Other parameters that are part of the standard model for foliar deposition, are the interception fraction, the crop yield (biomass), the translocation factor, the weathering half-life, and the growing period.

The interception fraction is the portion of the airborne contamination depositing in a unit area that initially attaches to vegetation. It includes the fraction of the ground surface that is covered by vegetation. Values for interception fraction for various crops are given in ORNL-5786. More recent publications described in PNNL-6584 (Section 4.7.4) will be used as the basis of the interception fractions for this performance assessment. The empirical relationship between interception fraction and standing biomass (dry weight) is shown below.

$$\text{Interception Fraction} = 1.0 - \text{Exp}[-(P)(\text{Dry Yield})]$$

The parameter P depends on the type of vegetation, as discussed in PNL-6584 Volume 1. For leafy vegetables, grains, grass and hay the measured value for P is 2.9 m^2/kg, while for fruits and other plants the measured value for P is 3.6 m^2/kg. The "Dry Yield" is the mass per unit area of the standing biomass at the time of harvest, adjusted for water content. The "Dry Yield" is calculated as the product of the dry-to-wet ratio and the crop yield (wet). Values for biomass and interception fraction are shown on the Table A39.

Table A39. Various Crop-Specific Parameters.

Type of Produce	Dry-to-wet Ratio	Crop Yield kg(wet)/m^2	Interception Fraction	Translocation Factor	Growing Period
Generic Vegetables	0.2	2	0.5	0.2	60 d
Leafy Vegetables	0.09	2.0	0.407	1.0	45 d
Other (protected)	0.25	2.0	0.835	0.1	90 d
Fruit (exposed)	0.18	3.0	0.857	0.1	90 d
Grains	0.20	0.8	0.371	0.1	90 d
Fresh Forage - Cow	0.22	1.5	0.616	1.0	30 d
Stored Hay - Cow	0.22	1.0	0.472	1.0	45 d
Stored Grain - Cow	0.91	1.0	0.472	0.1	90 d
Forage - Poultry	0.22	1.0	0.472	1.0	30 d
Grain - Poultry	0.91	1.0	0.472	0.1	90 d

Notes:
- The “Generic Vegetables” is used in the calculations for chemicals.
- The dry-to-wet ratio for leafy vegetables is from PNWD-2023. All other values are from NUREG/CR-5512 Section 6.5.7.
- Interception fractions are calculated using the formula described in the text (PNNL-6584 Section 4.7.4).

The translocation factor is the fraction of what deposits on the foliage that reaches the edible parts of the plant. The values are shown on Table A39 are widely used in calculations of this type (NRC 1977; PNNL-6584 1988; NUREG/CR-5512 1992) and will be used in the tank waste PA. The value shown for “Generic Vegetables” is used in the calculations for chemicals. It is selected so that the consumption weighted mass of soil deposited on the foliage is the same as for the total leafy, protected, and exposed crops used with radionuclides in the all pathways exposure scenario.

The weathering half-life is the time required for half the contamination initially deposited on plant foliage to be removed by the action of wind, rain and irrigation. The value chosen for both chemicals and radionuclides is 14 days, based on the recommendations of NRC (1977) and the review given in ORNL-5786.

The growing period is the time that a plant is subject to the mechanical action of weathering prior to be harvested. The growing period varies with crop type. It is the time needed to produce one crop. During the irrigation season more than one crop may be harvested.

A5.3 Direct Deposition

The models for root uptake and rain splash contributions to growing plants depend only on the soil concentration at the time of harvest. Direct deposition is unique to overhead irrigation. It refers to the transfer of contamination from irrigation water to the foliage intercepting the water as it falls.

A key parameter to model the contamination of foliage by direct deposition is the interception fraction. The value recommended for all plant types by the NRC (1977) will be used, 0.25. This value is not well documented, but is widely used in other reviews (PNNL-6584 1988; NUREG/CR-5512 1992).

The other parameters determining plant concentrations exposed to contaminated irrigation water are the translocation factors, the weathering half-life, and the growing periods. The same parameters used for describing rain splash will also be used for direct deposition. The translocation factors and growing periods are shown on Table A39, while the weathering half-life is 14 days.

If a special group of people were using overhead irrigation to increase growth density and crop yield, then the same parameters used for the standard group would apply to them also. No special modeling would be required unless the individuals were using the crop in some manner that could produce more dose than simply eating it.

A6.0 SOIL PARAMETERS

The soil parameters of interest are those pertaining to the various exposure pathways and to retention of contaminants that have been introduced by spreading exhumed waste, or irrigation with contaminated water. The two main types of exposure are from external and internal sources. In addition, the internal exposure can be divided into inhalation and ingestion intakes. Each of these routes of exposure will be discussed below.

The principal effect of the soil on the external radiation exposure received by someone living nearby is through the soil density, chemical composition, and roughness. The surface soil density is assumed to be 1.5 g/cc. The contamination of interest is distributed through the top 15 cm. The assumed composition is primarily silicon dioxide, with various additions, such as water. Over time the radioactive contaminants have been observed to migrate into deeper layers. The radioactive elements are affected by the average flow of water through the surface layer into deeper layers. Some elements, such as hydrogen and iodine are very soluble and leach from the surface layer in a few years. Other elements, such as cesium and plutonium hardly move at all.

The principal relationship between soil contamination and inhalation dose is through the ease with which contaminants in the soil become airborne. The presence of ground cover and moisture reduces the air concentration. Hand-tilling activities increase the air concentration. The gradual leaching of radioactive contamination to deeper layers of soil reduces the air concentration as well. The particle size distributions of the soil and any exhumed waste are important indicators of whether the mass-loading approach for estimating air concentrations could bias the expected contaminant concentration. If the contaminants tend to be found in the smaller particles, then the air concentration of contaminants would be higher than predicted because the average concentration in soil would be lower than the average concentration in dust.

The principal relationship between soil contamination and ingestion dose is through the ease with which contaminants in the soil become incorporated in plant and animal produce. It is assumed that the effects of tilling and fertilizers lead to soils that are similar to those for which the concentration ratios shown in Tables A37 and A38 were derived. The gradual leaching of contaminants into deeper layers of soil (below the root zone) reduces the concentration in plant and animal products as well. An additional consideration is how easily the contaminants adhere to exposed skin. Better adherence leads to increased dermal absorption.

A6.1 Leaching from the Surface Layer

Soil-specific parameters related to leaching are the soil composition (sand, clay, silt and organic), the distribution coefficients, the density, porosity, and the water content. The composition of the surface layer is assumed to be sandy, where sandy is defined to have greater than 70 percent sand-sized particles. With few exceptions this is what lies near the surface of the entire Hanford Site. The soil-to-plant concentration ratios and distribution coefficients depend on this assumption. However, the preparation of the soil for a garden changes the properties of surface layer. The tilling, watering and addition of fertilizers and organic material produces soil that tends to reduce the mobility of contaminants.

Leaching factors and distribution coefficients for chemicals are shown in Table A38. The value for the cyanide ion (CAS 57-12-5) is from Table C-4 in the EPA *Soil Screen Guidance User's Guide* (EPA/540/R-96/018). Values for other organic chemicals were calculated from the organic carbon partition coefficient shown in Table A38. The formula used is shown below. The carbon fraction in garden soil is 0.03 from Table A34. This is larger than the various values found in EPA soil documents, which is conservative as it leads to less leaching from the surface soil layer with time. The distribution coefficients for inorganic chemicals were taken from Table A40. Because nitrate, nitrite, and chromium (VI) are very mobile, the Kd for tritium shown in Table A40 (0.7 ml/g) was assumed to apply. Thus, the leaching coefficients for nitrate, nitrite, and chromium (VI) are all 0.533.

$$K_d = (0.03)\, K_{OC}$$

Leaching factors and distribution coefficients for radionuclides are shown in Table A40. The hierarchy used for selecting values was first the Hanford-specific values for agricultural soils in PNNL-14041. For elements with no values in PNNL-14041, IAEA Technical Report Number 364 was used. Sandy soil was used to represent the Hanford area. The next report consulted was ORNL-5786. Last of all came NUREG/CR-5512. The values shown for iodine lie within the range of possible values given in PNWD-2023, so PNWD-2023 was not needed.

Leaching factors and distribution coefficients for berkelium (Bk) were assumed to be the same as those for americium (Am), because none of the references supplied any values for berkelium.

The thickness of the surface soil of interest in the dose calculations is the top 15 centimeters. This thickness represents typical cultivation depths for mechanical mixing of deposited activity. In addition, it represents typical root depths. This thickness has been used in all prior Hanford Site performance assessments.

Table A40. Leaching Factors for Radionuclides in Garden Soil.

Element	Leach (per year)	Kd	Atomic Number	Element	Leach (per year)	Kd	Atomic Number
H	na	0.70 a	1	Cd	6.00E-03	74 b	48
Be	1.85E-03	240 b	4	In	2.96E-04	1,500 c	49
B	1.42E-01	3.0 c	5	Sn	4.94E-04	900 a	50
C	6.23E-02	7.0 a	6	Sb	8.89E-05	5,000 a	51
F	2.96E-03	150 c	9	Te	1.48E-03	300 c	52
Na	4.44E-03	100 c	11	I	2.94E-02	15 a	53
Al	2.96E-04	1,500 c	13	Cs	2.22E-04	2,000 a	55
Si	1.34E-02	33 b	14	Ba	7.39E-03	60 c	56
P	4.87E-02	9.0 b	15	Pm	6.84E-04	650 c	61
Cl	3.92E-01	1.0 a	17	Sm	1.85E-03	240 b	62
K	4.39E-02	10 a	19	Eu	6.84E-04	650 c	63
Ca	4.87E-02	9.0 b	20	Gd	6.84E-04	650 c	64
Ti	4.44E-04	1,000 c	22	Ho	1.85E-03	240 b	67
V	4.44E-04	1,000 c	23	Re	5.55E-03	80 a	75
Mn	1.85E-04	2,400 a	25	Hg	4.39E-02	10 c	80
Fe	1.27E-04	3,500 a	26	Tl	2.96E-04	1,500 c	81
Co	7.39E-03	60 b	27	Pb	5.56E-06	80,000 a	82
Ni	1.85E-04	2,400 a	28	Bi	4.94E-04	900 a	83
As	2.22E-03	200 c	33	Po	4.04E-04	1,100 a	84
Se	2.08E-01	2.0 a	34	Ra	8.89E-04	500 a	88
Rb	8.06E-03	55 b	37	Ac	2.96E-04	1,500 a	89
Sr	2.47E-03	180 a	38	Th	7.41E-07	600,000 a	90
Y	2.96E-04	1,500 a	39	Pa	1.23E-04	3,600 a	91
Zr	7.41E-04	600 b	40	U	6.23E-02	7.0 a	92
Nb	2.78E-03	160 b	41	Np	1.77E-02	25 a	93
Mo	5.90E-02	7.4 b	42	Pu	8.89E-05	5,000 a	94
Tc	2.08E-01	2.0 a	43	Am	2.96E-04	1,500 a	95
Ru	8.89E-04	500 a	44	Cm	2.96E-04	1,500 a	96
Pd	8.06E-03	55 b	46	Bk	2.96E-04	1,500 a	97
Ag	4.93E-03	90 b	47	Cf	8.71E-04	510 d	98

Table A40. Leaching Factors for Radionuclides in Garden Soil.

Element	Leach (per year)	Kd	Atomic Number	Element	Leach (per year)	Kd	Atomic Number
Notes: • These distribution coefficients were selected using the following hierarchy: (a) PNNL-14041, (b) IAEA Technical Report Number 364, (c) ORNL-5786, and (d) NUREG/CR-5512. The leaching coefficient for hydrogen is not used in the calculations (na). • Note that the distribution coefficient for Bk is assumed to be the same as Am.							

The density and thickness of the affected surface layer determine the external dose rate factors, as well as the leaching coefficients computed for the surface layer. Leaching is the process by which contaminants migrate from the surface layer of soil into deeper layers below. The driving force behind the leaching process is the application of water to the soil. Leaching is treated as a removal rate constant giving the fraction of the material in the surface layer that is removed per unit of time. It is calculated using the equation shown below.

$$\lambda_S = \frac{P + I - E}{\theta\, d \left(1 + \rho K_d / \theta\right) T_{irr}}$$

where,

- d = thickness of the surface soil layer from which nuclides migrate, 15 cm (5.9 inches).
- E = total evapo-transpiration during the irrigation season, in cm. For the population scenario a value of 59.27 cm is assumed. For the other scenarios a value 78.06 cm is assumed. These assumptions lead to a total over-irrigation (P+I-E) of 10 cm. This over-irrigation assumption is consistent with PNWD-2023, which assumed that farmers over-irrigate by 10 percent.
- I = total irrigation water applied during the irrigation season, in cm. For the population scenarios this is 63.5 cm (25 in.). For the other scenarios it is 82.3 cm (32.4 inches). Nearly all of this is deposited during the 6 month period from April to September.
- K_d = distribution coefficient in surface soil for an element, in ml/g. Values for chemicals are shown on Table A38. Values for radionuclides are shown in Table A40.
- P = total precipitation, in centimeters, during the irrigation period. Over the period 1971 to 2000, the precipitation during the 6 month irrigation season (April to September) has been 5.766 cm (PNNL-13859).
- T_{irr} = irrigation period, 0.5 y
- λ_S = average soil leaching coefficient, fraction removed from a soil layer of thickness "d" during the time that irrigation occurs, per year.
- ρ = bulk density of the surface soil, 1.5 g/cc.
- θ = volumetric water content of the surface soil, milliliters of water per cubic centimeter of soil. A value of 0.2 ml/cc is assumed. Because the total soil porosity is about 0.4 ml/cc, the saturation ratio is about 50%.

The values assigned to the variables in the above equation were used in prior Hanford performance assessments. The annual irrigation total (82.3 cm/y) is based on the Specific

Information on the Terrestrial Environment (SITE) database referenced ORNL-5786. The SITE database reports that a large percentage of the drier western states falls into the range from 70 to 85 cm/y. The values chosen in NUREG/CR-5512 is 76 cm/y, while the value more appropriate to Hanford is 82.3 cm/y (WHC-SD-WM-EE-004). The Hanford value is based on irrigation rates in the counties surrounding the site. Note that the amount of irrigation is assumed to be the same for all plant types including grains.

For the population living along the Columbia River, the annual irrigation amount is reduced to account for the greater precipitation closer to the ocean. In addition, the average irrigation rate along the river is 25 in/y (63.5 cm/y) (WHC-SD-WM-EE-004). This value was obtained as an average in counties along the Columbia River, and thereby differs from the irrigation rate assumed for individuals living near the Hanford Site. Because this average is over a large population it will have an insignificant range.

Leaching coefficients computed from the above equation are listed in Table A40 along with the distribution coefficient. The numerator represents the excess water added each year. It is taken to be about 10 cm during the irrigation season based on the discussion in PNWD-2023.

The Hanford Environmental Dose Reconstruction Project (HEDR) found the irrigation rate in the counties surrounding the Hanford Site ranged from 61 cm/y to 98 cm/y (PNWD-2023, Rev 1). The excess watering term in the numerator (P+I-E) then ranges from 0 to 26 cm/y, and the leaching coefficients range from 0 to 2.5 times the chosen values. This range has little effect on the resulting doses for most nuclides because the leaching coefficients are generally small.

The leaching factor for tritium includes both evaporation as well as percolation out of the surface layer. The evaporative losses are estimated assuming the soil gains no water. Thus, the amount deposited as irrigation or precipitation is the amount that leaves. During the irrigation season, April through September, there is 5.77 cm precipitation (PNNL-13859). The remainder of the year the precipitation average is 11.96 cm. Irrigation is 82.3 cm for the individuals, and 63.5 for the Columbia River population. The effective leaching coefficient for water during the irrigation months is 46.18 per year for the population and 58.71 per year for the individuals. During the non-irrigation months the effective leaching coefficient is 7.975 per year. These are calculated using the equations below. The numerators in both cases are the amount of evaporation that is assumed. The variables were defined in previous equations.

$$\begin{aligned} \text{Tritium Emanation} &= \frac{P + I - 10\text{ cm/y}}{\theta\, d\, T_{irr}} \quad \text{during irrigation months} \\ &= \frac{P}{\theta\, d\, T_{no}} \quad \text{during non-irrigation months} \end{aligned}$$

A6.2 Garden Soil Concentration

A two-part removal rate from the soil has been adopted for use in the tank waste PA. It is assumed that significant irrigation occurs during 6 months of the year. The rest of the year has very little water infiltration. During the no-irrigation period there is no leaching from the surface layer. Tritium is an exception that is discussed below.

In the post-intrusion residential scenario, the irrigation water is free of contaminants and acts to reduce the surface soil concentration. The surface soil concentration decreases exponentially with time. The removal constant is the sum of the leaching coefficient and the decay coefficient. The equation below shows the factor that is applied to the initial garden soil concentration to calculate the concentration at the end of the year.

$$F_{NS} = \mathrm{Exp}(-\lambda\, T_{irr})\ \mathrm{Exp}(-\lambda_R\, T_{no})$$
$$\text{and} \quad \lambda = \lambda_S + \lambda_R \quad \text{and} \quad T_{irr} + T_{no} = 1\ \mathrm{y}$$

where,

- F_{NS} = fraction of the initial soil concentration that is left at the end of 1 year when the irrigation water adds no contaminants
- T_{irr} = irrigation period, 0.5 y
- T_{no} = no irrigation period, 1 y - T_{irr} = 0.5 y
- λ = total removal constant, per year
- λ_R = radioactive decay or chemical decomposition constant, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).
- λ_S = average soil leaching coefficient, fraction removed from a soil layer of thickness "d", per year

Each year the same factor is applied to calculate the soil concentration at the end of the year. Thus the soil concentration after N years is F_{NS} raised to the Nth power.

The initial tritium concentration in soil decreases according to the above formula, with one exception. During the no-irrigation season, the removal constant (8.032 per year) is the decay constant (0.05622 per year for tritium) plus the evaporation constant (7.975 per year).

In the various irrigation scenarios, the irrigation water is contaminated and adds to the surface soil concentration. The surface soil concentration increases during the irrigation season, and decreases during the no-irrigation season. The equation below shows the factor that is applied to the irrigated soil total concentration (amount deposited per unit area during the year divided by the area density of the soil) to calculate the concentration at the end of the year.

$$F_{IS} = \frac{1 - \mathrm{Exp}(-\lambda\, T_{irr})}{\lambda\, T_{irr}}\ \mathrm{Exp}(-\lambda_R\, T_{no})$$
$$\text{and} \quad \lambda = \lambda_S + \lambda_R \quad \text{and} \quad T_{irr} + T_{no} = 1\ \mathrm{y}$$

where,

- F_{IS} = fraction of the total soil concentration (amount deposited per unit area during the year divided by the area density of the soil) that is present at the end of 1 year when the irrigation water is adding contaminants to the soil
- T_{irr} = irrigation period, 0.5 y
- T_{no} = no irrigation period, 1 y - T_{irr} = 0.5 y
- λ = total removal constant, per year
- λ_R = radioactive decay or chemical decomposition constant, per year. These are calculated as ln(2)=0.6931472 divided by the material half life (in years).

λ_S = average soil leaching coefficient, fraction removed from a soil layer of thickness "d", per year

Each year the same amount is added to the soil by ongoing irrigation, and the amounts deposited in prior years decrease by the factor F_{NS} each year. After N years of irrigation, the soil concentration is the total soil concentration (amount deposited per unit area during one year divided by the area density of the soil) times the factor shown below.

$$F_{IS}\,\frac{1-\left(F_{NS}\right)^{N}}{1-F_{NS}}$$

Natural precipitation acts to dilute contaminated irrigation water slightly. It adds water that is not contaminated. The formula below shows the dilution factors [i.e., I/(I+P)] used in these calculations during the irrigation season. These factors are used wherever F_{IS} is used.

Dilution Adjustment (individual) = (82.3 cm)/(82.3 + 5.77 cm) = 0.9345

Dilution Adjustment (population) = (63.5 cm)/(63.5 + 5.77 cm) = 0.9168

The tritium concentration in irrigated soil is calculated using an equilibrium model. The tritium is chemically bound in a water molecule and thus goes with the water. The concentration of tritium in irrigation water, is similar to the concentration in the water in the soil. The soil hydrogen fraction is 0.0149 kg hydrogen per kg soil, as shown in Table A34. Thus the effective moisture content of the soil is calculated as shown below. The density of water is 1.0 kg/L.

(8.94 g H_2O/g H_2)(0.0149 kg H_2/kg soil)/(1.0 kg/L) = 0.133 L H_2O/kg soil

This value may also be calculated from the assumed value for the volumetric water content of soil (0.2 ml/cc) and its density (1.5 kg/L). Note that the value reported in NUREG/CR-5512 is 0.1 L/kg. A somewhat higher value is being used in the tank waste PA, which leads to higher tritium concentrations in soil during the irrigation season.

The tritium concentration in irrigated soils during the irrigation season is this soil water concentration times the concentration of tritium in the irrigation water times the natural precipitation dilution fraction. During the non-irrigation season the tritium concentration decreases exponentially using the evaporation plus decay removal constant (8.032 per year) discussed above. By the end of the year, the tritium concentration is essentially zero. Thus, there is no accumulation of tritiated water in soil in the present model.

A6.3 Shoreline Sediment Concentration

Shoreline sediments accumulate contaminants present in river water much the same as garden soil. A simple model to represent this accumulation is based on models from BNWL-1754 and NCRP Report No. 76. In the former, the accumulated sediment concentration depends on the water concentration, a deposition factor, and the radioactive half life. In the latter, the accumulation depends only on the water concentration and the distribution coefficient for sediment. The model chosen for these calculations is a combination of the two and is shown below.

$$C_D = \frac{C_W\,V_S}{\rho\,d\,\lambda}\left[1 - \mathrm{Exp}(-\lambda\,T)\right] \qquad \text{and} \qquad \lambda = \lambda_S + \lambda_R$$

where,

C_D = concentration of the contaminant in shoreline sediment, in Ci/kg
C_W = concentration of the contaminant in the river water, in Ci/L
d = thickness of the shoreline sediment layer that holds the contaminants, 15 cm (5.9 inches) assumed
T = time at which the sediment concentration is calculated, in years
V_S = effective river to sediment deposition rate, 25,300 L/m^2 per year (BNWL-1754 and PNNL-6584)
λ = total removal constant, per year
λ_R = decay or decomposition constant, per year
λ_S = average soil leaching coefficient, fraction removed from a soil layer of thickness "d", per year
ρ = bulk density of the shoreline sediment layer, 1.5 g/cc assumed

If the product (λT) is small, the sediment concentration grows linearly with time. If this product is large, the sediment concentration is proportional to the inverse of the total removal constant (λ), which depends on both the decay half life and the distribution coefficient. In general, sediment concentrations are much larger than garden soil concentrations. For an irrigation rate of 82.3 cm/y, there is 823 L/m^2 applied by irrigation each year. The shoreline sediment increases by 25,300 L/m^2 each year, a factor of 30 greater.

A6.4 Volatile Emissions from the Soil Surface

Chemicals dissolved in water that is applied to the soil for irrigation purposes will evaporate much like the water does. A simple model to represent this process was developed by Jury, et al. (1983, 1984, and 1990). EPA has adopted a simplified version for estimating inhalation dose from volatile chemical emissions from the soil surface (EPA/540/R95/128). The simple model represents the time dependence of a layer of surface soil that is initially contaminated at some uniform concentration (C_0). The formula for the fractional loss rate from the surface layer as a function of time is shown below.

$$\lambda_V = \frac{J_S}{\rho\,d\,C_0} = \frac{1}{d}\sqrt{\frac{D_E}{\pi\,T}}\left[1 - \mathrm{Exp}\left(\frac{-d^2}{4\,D_E\,T}\right)\right]\mathrm{Exp}(-\lambda_R\,T)$$

$$D_E = \frac{\theta^{10/3}\,D_W + (\theta_A)^{10/3}\,D_A\,H'}{(\rho\,K_d + \theta + \theta_A\,H')\varphi^2}$$

where,

C_0 = initial soil concentration, in g/kg
d = thickness of the surface layer that holds the contaminants, 15 cm (5.9 inches) assumed

D_A = diffusion coefficient for the chemical vapor in air from Table A41, cm^2/s
D_E = effective diffusion coefficient for contaminant motion from the soil and soil water into the soil air, cm^2/y
D_W = diffusion coefficient for the chemical dissolved in water from Table A41, cm^2/s
T = time at which the chemical loss rate is calculated, in years
H' = unitless Henry's Law Constant for the chemical from Table A3
J_S = mass flux of the chemical out of the soil surface, in g/cm^2 per year
K_d = distribution coefficient for the chemical in surface soil, in ml/g. Values for chemicals are shown on Table A38.
φ = total soil porosity, in ml/cm^3. $\varphi = 1 - \rho/\rho_p = 0.40\ ml/cm^3$
λ_V = volatile emanation constant for the chemical, or fractional loss rate from the surface soil layer into the air above the soil, per year
λ_R = decomposition constant for the chemical, per year (assumed zero)
ρ = bulk density of the surface soil layer, 1.5 g/cm^3 assumed
ρ_p = particle density of the surface soil layer, 2.5 g/cm^3 assumed
θ = volumetric water content of the surface soil, milliliters of water per cubic centimeter of soil. A value of 0.2 ml/cm^3 is assumed.
θ_A = volumetric air content of the surface soil, milliliters of air per cubic centimeter of soil. $\theta_A = \varphi - \theta$

The loss rate decreases with time. Thus, an average loss rate is calculated by performing the time integral of the above formula divided by the averaging time (T_{AVE}). The average loss rate (or emanation constant) assuming no decomposition (λ_R=0) is shown in the equation below.

$$\lambda_V = \frac{2}{d}\sqrt{\frac{D_E}{\pi\, T_{AVE}}}\left[1 - \mathrm{Exp}\left(\frac{-d^2}{4\, D_E\, T_{AVE}}\right)\right] + \frac{1}{T_{AVE}}\mathrm{ERFC}\left(\frac{d}{2\sqrt{D_A\, T_{AVE}}}\right)$$

Values for the diffusion coefficients (D_A and D_W) are shown in Table A41 along with the emanation constants (λ_V). Irrigated fields are represented as a series of contamination events. Active watering of the soil lasts less than an hour. The averaging period is taken to be the time between irrigation additions to the soil. Because the emanation constant decreases with time, the longest averaging time possible was used, namely, 168 hours (1 week). During the non-irrigation period, the emanation constants are calculated using an averaging period of 0.5 year.

Table A41. Diffusion Coefficients and Emanation Constants

CASRN	Chemical	Diffusion Coefficients (cm^2/sec) Air	Diffusion Coefficients (cm^2/sec) Water	Emanation Constants (per year) Active Irrigation	Emanation Constants (per year) No Irrigation
50-32-8	Benzo[a]pyrene	4.30E-02	9.00E-06	8.70E-03	1.70E-03
53-70-3	Dibenz[a,h]anthracene	2.02E-02	5.18E-06	3.50E-03	6.83E-04
56-23-5	Carbon tetrachloride	7.80E-02	8.80E-06	4.35E+01	1.93E+00
57-12-5	Cyanide, free	na	na	4.43E-02	0.00E+00
57-14-7	1,1-Dimethylhydrazine	1.06E-01	1.09E-05	2.28E+00	3.27E-01
57-55-6	Propylene glycol (1,2-Propanediol)	9.30E-02	1.02E-05	6.09E+00	6.55E-01
58-89-9	gamma-Benzene hexachloride (gamma-Lindane)	1.42E-02	7.34E-06	1.40E-01	2.66E-02

Table A41. Diffusion Coefficients and Emanation Constants

CASRN	Chemical	Diffusion Coefficients (cm^2/sec) Air	Diffusion Coefficients (cm^2/sec) Water	Emanation Constants (per year) Active Irrigation	Emanation Constants (per year) No Irrigation
60-34-4	Methylhydrazine	2.53E-01	1.39E-05	2.63E+00	3.85E-01
60-57-1	Dieldrin	1.25E-02	4.74E-06	7.63E-02	1.47E-02
62-75-9	N-Nitrosodimethylamine	1.13E-01	1.24E-05	2.06E+00	3.36E-01
64-18-6	Formic acid	7.90E-02	1.37E-06	4.18E+00	2.85E-01
67-56-1	Methanol (Methyl alcohol)	1.50E-01	1.64E-05	9.73E+00	1.16E+00
67-64-1	Acetone (2-Propanone)	1.24E-01	1.14E-05	1.64E+01	1.55E+00
67-66-3	Chloroform	1.04E-01	1.00E-05	3.57E+01	1.87E+00
71-36-3	n-Butyl alcohol (n-Butanol)	8.00E-02	9.30E-06	7.93E+00	1.03E+00
71-43-2	Benzene	8.80E-02	9.80E-06	2.50E+01	1.76E+00
71-55-6	1,1,1-Trichloroethane (Methyl chloroform)	7.80E-02	8.80E-06	4.14E+01	1.92E+00
72-20-8	Endrin	1.25E-02	4.74E-06	6.89E-02	1.32E-02
74-83-9	Bromomethane	7.28E-02	1.21E-05	4.17E+01	1.91E+00
74-87-3	Methyl chloride (Chloromethane)	1.26E-01	6.50E-06	4.56E+01	1.94E+00
75-00-3	Ethyl Chloride	2.71E-01	1.15E-05	4.72E+01	1.96E+00
75-01-4	Vinyl chloride (Chloroethene)	1.06E-01	1.23E-06	4.69E+01	1.96E+00
75-05-8	Acetonitrile	1.28E-01	1.66E-05	1.32E+01	1.46E+00
75-07-0	Acetaldehyde	1.24E-01	1.41E-05	2.12E+01	1.66E+00
75-09-2	Dichloromethane (Methylene chloride)	1.01E-01	1.17E-05	3.72E+01	1.88E+00
75-15-0	Carbon disulfide	1.04E-01	1.00E-05	5.08E+01	1.97E+00
75-21-8	Ethylene Oxide (Oxirane)	1.04E-01	1.45E-05	2.68E+01	1.75E+00
75-34-3	1,1-Dichloroethane (Ethylidene chloride)	7.42E-02	1.05E-05	3.63E+01	1.87E+00
75-35-4	1,1-Dichloroethylene	9.00E-02	1.04E-05	4.50E+01	1.94E+00
75-45-6	Chlorodifluoromethane	8.30E-02	1.28E-05	4.61E+01	1.95E+00
75-68-3	Chloro-1,1-difluoroethane, 1-	na	na	2.79E-01	0.00E+00
75-69-4	Trichlorofluoromethane	8.70E-02	9.70E-06	4.74E+01	1.96E+00
75-71-8	Dichlorodifluoromethane	5.20E-02	1.05E-05	4.80E+01	1.97E+00
76-13-1	1,1,2-Trichloro-1,2,2-trifluoroethane (CFC-113)	2.88E-02	8.07E-06	4.42E+01	1.94E+00
76-44-8	Heptachlor	1.12E-02	5.69E-06	1.27E-01	2.49E-02
78-87-5	1,2-Dichloropropane	7.82E-02	8.73E-06	2.57E+01	1.76E+00
78-93-3	Methyl ethyl ketone (2-Butanone)	8.08E-02	9.80E-06	1.38E+01	1.48E+00
79-00-5	1,1,2-Trichloroethane	7.80E-02	8.80E-06	1.50E+01	1.57E+00
79-01-6	Trichloroethylene	7.90E-02	9.10E-06	3.63E+01	1.87E+00
79-10-7	2-Propenoic acid (Acrylic acid)	9.80E-02	1.06E-05	6.22E+00	6.97E-01
79-34-5	1,1,2,2-Tetrachloroethane (Acetylene tetrachloride)	7.10E-02	7.90E-06	7.77E+00	1.22E+00
82-68-8	Pentachloronitrobenzene (PCNB)	1.59E-02	6.14E-06	3.02E-01	5.79E-02
83-32-9	Acenaphthene	4.21E-02	7.69E-06	5.65E-01	1.10E-01
84-66-2	Diethyl phthalate	2.56E-02	6.35E-06	6.82E-01	1.11E-01
84-74-2	Dibutyl phthalate	4.38E-02	7.86E-06	2.24E-01	4.19E-02
85-68-7	Butyl benzyl phthalate	1.74E-02	4.83E-06	6.24E-02	1.19E-02
87-68-3	Hexachlorobutadiene	5.61E-02	6.16E-06	1.20E+01	1.48E+00
87-86-5	Pentachlorophenol	5.60E-02	6.10E-06	1.09E-01	2.05E-02

Table A41. Diffusion Coefficients and Emanation Constants

CASRN	Chemical	Diffusion Coefficients (cm^2/sec) Air	Diffusion Coefficients (cm^2/sec) Water	Emanation Constants (per year) Active Irrigation	Emanation Constants (per year) No Irrigation
88-06-2	2,4,6-Trichlorophenol	3.18E-02	6.25E-06	2.34E-01	4.33E-02
88-85-7	2-sec-Butyl-4,6-dinitrophenol (Dinoseb)	na	na	4.18E-03	0.00E+00
91-20-3	Naphthalene	5.90E-02	7.50E-06	1.88E+00	3.67E-01
92-52-4	1,1'-Biphenyl	4.04E-02	8.15E-06	7.09E-01	1.38E-01
95-50-1	1,2-Dichlorobenzene (ortho-)	6.90E-02	7.90E-06	8.59E+00	1.29E+00
95-63-6	1,2,4-Trimethylbenzene	6.44E-02	7.92E-06	1.17E+01	1.46E+00
98-86-2	Acetophenone	6.00E-02	8.73E-06	2.31E+00	3.96E-01
98-95-3	Nitrobenzene	7.60E-02	8.60E-06	1.68E+00	3.14E-01
100-25-4	1,4-Dinitrobenzene (para-)	na	na	6.60E-02	0.00E+00
100-41-4	Ethyl benzene	7.50E-02	7.80E-06	1.66E+01	1.62E+00
100-42-5	Styrene	7.10E-02	8.00E-06	9.64E+00	1.36E+00
100-51-6	Benzyl alchohol	7.12E-02	8.97E-06	2.47E+00	3.39E-01
106-46-7	1,4-Dichlorobenzene (para-)	6.90E-02	7.90E-06	9.72E+00	1.37E+00
106-93-4	1,2-Dibromoethane (Ethylene dibromide)	2.17E-02	1.19E-05	8.99E+00	1.30E+00
106-99-0	1,3-Butadiene	2.49E-01	1.08E-05	4.93E+01	1.98E+00
107-02-8	Acrolein	1.05E-01	1.22E-05	2.27E+01	1.70E+00
107-05-1	3-Chloropropene (Allyl chloride)	1.17E-01	1.08E-05	4.18E+01	1.92E+00
107-06-2	1,2-Dichloroethane (Ethylene chloride)	1.04E-01	9.90E-06	2.41E+01	1.74E+00
107-13-1	Acrylonitrile	1.22E-01	1.34E-05	1.92E+01	1.65E+00
108-10-1	Methyl isobutyl ketone (4-Methyl-2-pentanone)	7.50E-02	7.80E-06	1.40E+01	1.52E+00
108-67-8	1,3,5-Trimethylbenzene	6.02E-02	8.67E-06	1.36E+01	1.53E+00
108-87-2	Methyl cyclohexane	9.86E-02	8.52E-06	4.72E+01	1.96E+00
108-88-3	Toluene (Methyl benzene)	8.70E-02	8.60E-06	2.21E+01	1.72E+00
108-90-7	Chlorobenzene	7.30E-02	8.70E-06	1.44E+01	1.56E+00
108-94-1	Cyclohexanone	7.84E-02	8.62E-06	4.16E+00	6.61E-01
108-95-2	Phenol (Carbolic acid)	8.20E-02	9.10E-06	5.31E-01	9.33E-02
110-00-9	Furan (Oxacyclopentadiene)	1.04E-01	1.22E-05	3.16E+01	1.83E+00
110-54-3	n-Hexane	2.00E-01	7.77E-06	5.02E+01	1.98E+00
110-86-1	Pyridine	9.10E-02	7.60E-06	3.19E+00	5.47E-01
111-76-2	2-Butoxyethanol (Ethylene Glycol Monobutyl Ether)	6.51E-02	8.15E-06	6.43E+00	7.18E-01
111-90-0	2-(2-Ethoxyethoxy)-ethanol (Diethylene Glycol Monoethyl Ether)	5.24E-02	8.02E-06	5.71E+00	5.83E-01
117-81-7	Di (2-ethylhexyl) phthalate (DEHP)	3.51E-02	3.66E-06	1.23E-02	2.38E-03
117-84-0	Di-n-octylphthalate	1.51E-02	3.58E-06	1.27E-02	2.48E-03
118-74-1	Hexachlorobenzene	5.42E-02	5.91E-06	2.60E+00	5.08E-01
120-82-1	1,2,4-Trichlorobenzene	3.00E-02	8.23E-06	3.85E+00	7.38E-01
121-44-8	Triethylamine	8.81E-02	7.88E-06	5.56E+00	9.85E-01
122-39-4	Diphenylamine	na	na	7.83E-03	0.00E+00
123-91-1	1,4-Dioxane (Diethylene oxide)	2.29E-01	1.02E-05	1.05E+01	1.24E+00
126-73-8	Tributyl Phosphate	na	na	7.83E-03	0.00E+00
126-98-7	2-Methyl-2-propenenitrile (Methacrylonitrile)	8.45E-02	1.06E-05	1.81E+01	1.63E+00

Table A41. Diffusion Coefficients and Emanation Constants

CASRN	Chemical	Diffusion Coefficients (cm^2/sec)		Emanation Constants (per year)	
		Air	Water	Active Irrigation	No Irrigation
127-18-4	1,1,2,2-Tetrachloroethylene	7.20E-02	8.20E-06	3.66E+01	1.88E+00
141-78-6	Ethyl acetate (Acetic acid, ethyl ester)	7.32E-02	9.66E-06	1.67E+01	1.58E+00
156-59-2	cis-1,2-Dichloroethylene	7.36E-02	1.13E-05	3.21E+01	1.83E+00
206-44-0	Fluoranthene (1,2-Benzacenaphthene)	3.02E-02	6.35E-06	3.86E-02	7.52E-03
309-00-2	Aldrin	1.32E-02	4.86E-06	4.06E-02	7.93E-03
319-84-6	alpha-Benzene hexachloride (alpha-Lindane)	1.42E-02	7.34E-06	1.65E-01	3.14E-02
319-85-7	beta-Benzene hexachloride (beta-Lindane)	1.42E-02	7.34E-06	1.21E-01	2.28E-02
621-64-7	N-Nitrosodi-N-propylamine	5.45E-02	8.17E-06	5.29E-01	9.77E-02
1314-62-1	Vanadium pentoxide	na	na	4.44E-04	0.00E+00
1330-20-7	Xylenes (mixtures)	7.14E-02	9.34E-06	1.61E+01	1.61E+00
1336-36-3	Polychlorinated Biphenyls (high risk)	1.75E-02	8.00E-06	1.85E-01	3.62E-02
1336-36-3	Polychlorinated Biphenyls (low risk)	1.75E-02	8.00E-06	1.85E-01	3.62E-02
1336-36-3	Polychlorinated Biphenyls (lowest risk)	1.75E-02	8.00E-06	1.85E-01	3.62E-02
6533-73-9	Thallium carbonate	na	na	2.96E-04	0.00E+00
7429-90-5	Aluminum	na	na	2.96E-04	0.00E+00
7439-96-5	Manganese	na	na	1.85E-04	0.00E+00
7439-98-7	Molybdenum	na	na	5.90E-02	0.00E+00
7440-02-0	Nickel (soluble salts)	na	na	1.85E-04	0.00E+00
7440-22-4	Silver	na	na	4.93E-03	0.00E+00
7440-24-6	Strontium, Stable	na	na	2.47E-03	0.00E+00
7440-31-5	Tin	na	na	4.94E-04	0.00E+00
7440-36-0	Antimony	na	na	8.89E-05	0.00E+00
7440-38-2	Arsenic (inorganic)	na	na	2.22E-03	0.00E+00
7440-39-3	Barium	na	na	7.39E-03	0.00E+00
7440-41-7	Beryllium and compounds	na	na	1.85E-03	0.00E+00
7440-42-8	Boron and borates only	na	na	1.42E-01	0.00E+00
7440-43-9	Cadmium	na	na	6.00E-03	0.00E+00
7440-48-4	Cobalt	na	na	7.39E-03	0.00E+00
7440-66-6	Zinc and compounds	na	na	2.22E-03	0.00E+00
7487-94-7	Mercuric chloride	na	na	4.39E-02	0.00E+00
7664-41-7	Ammonia	na	na	7.90E-01	0.00E+00
7723-14-0	Phosphorus, white	na	na	4.87E-02	0.00E+00
7782-41-4	Fluorine (soluble fluoride)	na	na	2.96E-03	0.00E+00
7782-49-2	Selenium and compounds	na	na	2.08E-01	0.00E+00
8001-35-2	Toxaphene	1.16E-02	4.34E-06	2.11E-02	4.10E-03
14797-55-8	Nitrate	na	na	5.33E-01	0.00E+00
14797-65-0	Nitrite	na	na	5.33E-01	0.00E+00
16065-83-1	Chromium (III) (insoluble salts)	na	na	6.62E-03	0.00E+00
18540-29-9	Chromium (VI) (soluble salts)	na	na	5.33E-01	0.00E+00
none	Uranium (soluble salts)	na	na	6.23E-02	0.00E+00

Table A41. Diffusion Coefficients and Emanation Constants

		Diffusion Coefficients (cm^2/sec)		Emanation Constants (per year)	
CASRN	Chemical	Air	Water	Active Irrigation	No Irrigation

Notes:
- CASRN = Chemical Abstract Service Reference Number
- The averaging time is 1 week (168 hours).
- Missing values are indicated with "na", which means "not available".

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Attachment A1. ISCST3 Input Files for the 100 m^2 Source

First Case -- Zero Elevation Receptors

```
CO STARTING
   TITLEONE  Area Sources --- 100 sq.m
   MODELOPT  MSGPRO  CONC  RURAL
   AVERTIME  ANNUAL
   TERRHGTS  ELEV
   FLAGPOLE  0.0
   POLLUTID  OTHER
   RUNORNOT  RUN
   ERRORFIL  ERRORS.LST
CO FINISHED

SO STARTING
**          SRCID  SRCTYP    XS       YS        ZS
**          -----  ------   -----    -----     -----
   LOCATION  A100   AREA    -5.0     -5.0      .0000

**          SRCID    QS       HS     XINIT   YINIT
**          -----   ----     ----    -----   -----
   SRCPARAM  A100    1.0      0.0      10.     10.

   EMISUNIT    1.00  (GRAMS/(SEC-M**2))          grams/cubic-meter

   SRCGROUP   AREA1   A100
SO FINISHED

RE STARTING
   GRIDPOLR POL1 STA
                 DIST  1.  1.5  2.  2.5  3.  5.  10.  15.  20.
                 GDIR  36   0.0   10.0
   GRIDPOLR POL1 END
   DISCCART      0.     0.     0.     0.
   DISCCART      0.     0.     0.     1.
   DISCCART      0.    10.     0.     0.
   DISCCART      0.    10.     0.     1.
   DISCCART     10.    10.     0.     0.
   DISCCART     10.    10.     0.     1.
   DISCCART     10.     0.     0.     0.
   DISCCART     10.     0.     0.     1.
   DISCCART     10.   -10.     0.     0.
   DISCCART     10.   -10.     0.     1.
   DISCCART      0.   -10.     0.     0.
   DISCCART      0.   -10.     0.     1.
   DISCCART    -10.   -10.     0.     0.
   DISCCART    -10.   -10.     0.     1.
   DISCCART    -10.     0.     0.     0.
   DISCCART    -10.     0.     0.     1.
   DISCCART    -10.    10.     0.     0.
   DISCCART    -10.    10.     0.     1.
RE FINISHED

ME STARTING
   INPUTFIL  MET\EPA92-96.2E
   ANEMHGHT  10.0
```

```
   SURFDATA  67656  1992   Hanford-200
   UAIRDATA  67656  1992   Hanford-200
ME FINISHED

OU STARTING
   RECTABLE ALLAVE FIRST  SECOND
   MAXTABLE ALLAVE  50
OU FINISHED
```

Second Case -- 0.5 m Elevation Receptors

```
CO STARTING
   TITLEONE  Area Sources --- 100 sq.m
   MODELOPT  MSGPRO  CONC  RURAL
   AVERTIME  ANNUAL
   TERRHGTS  ELEV
   FLAGPOLE  0.5
   POLLUTID  OTHER
   RUNORNOT  RUN
   ERRORFIL  ERRORS.LST
CO FINISHED

SO STARTING
**          SRCID  SRCTYP    XS       YS        ZS
**          -----  ------   -----    -----     -----
   LOCATION  A100    AREA    -5.0     -5.0     .0000

**          SRCID    QS       HS     XINIT   YINIT
**          -----   ----     ----    -----   -----
   SRCPARAM  A100     1.0      0.0      10.     10.

   EMISUNIT     1.00  (GRAMS/(SEC-M**2))           grams/cubic-meter

   SRCGROUP    AREA1   A100
SO FINISHED

RE STARTING
   GRIDPOLR POL1 STA
                 DIST  3.  5.  6.  7.  8.  9.  10.  12.  15.
                 GDIR  36   0.0   10.0
   GRIDPOLR POL1 END
RE FINISHED

ME STARTING
   INPUTFIL  MET\EPA92-96.2E
   ANEMHGHT  10.0
   SURFDATA  67656  1992   Hanford-200
   UAIRDATA  67656  1992   Hanford-200
ME FINISHED

OU STARTING
   RECTABLE ALLAVE FIRST  SECOND
   MAXTABLE ALLAVE  50
OU FINISHED
```

Third Case -- 1 m Elevation Receptors

```
CO STARTING
   TITLEONE  Area Sources --- 100 sq.m
   MODELOPT  MSGPRO  CONC  RURAL
   AVERTIME  ANNUAL
   TERRHGTS  ELEV
   FLAGPOLE  1.0
   POLLUTID  OTHER
   RUNORNOT  RUN
   ERRORFIL  ERRORS.LST
CO FINISHED

SO STARTING
**          SRCID  SRCTYP    XS       YS        ZS
**          -----  ------   -----    -----     -----
   LOCATION  A100    AREA    -5.0     -5.0     .0000

**          SRCID    QS       HS     XINIT   YINIT
**          -----   ----     ----    -----   -----
   SRCPARAM  A100     1.0      0.0      10.     10.

   EMISUNIT     1.00  (GRAMS/(SEC-M**2))           grams/cubic-meter

   SRCGROUP    AREA1   A100
SO FINISHED

RE STARTING
   GRIDPOLR POL1 STA
                 DIST  8.  12.  13.  14.  15.  16.  17.  20.  25.
                 GDIR  36   0.0   10.0
   GRIDPOLR POL1 END
RE FINISHED

ME STARTING
   INPUTFIL  MET\EPA92-96.2E
   ANEMHGHT  10.0
   SURFDATA  67656  1992   Hanford-200
   UAIRDATA  67656  1992   Hanford-200
ME FINISHED

OU STARTING
   RECTABLE ALLAVE FIRST  SECOND
   MAXTABLE ALLAVE  50
OU FINISHED
```

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